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Section A

INTRODUCTION

This grant proposal describes the objectives for the research efforts of the Nuclear Physics Group of the University of New Hampshire (UNH). These objectives include experimental measurements, instrumentation development, and data interpretation through nuclear modelling. Achieving and maintaining a balance in these three areas allows our group to identify and follow up on key ideas and novel techniques that yield breakthroughs in electromagnetic nuclear physics. This balance is essential also for the education of our graduate students.

The DOE has generously supported the nuclear physics group at UNH for twelve years. During this period of time, we have grown from an initial size of two faculty, one postdoctoral scientist, and one or two students to a working group consisting of four faculty, two postdoctoral scientists, and three or four students. Graduate student education is an important part of our operations. In the past three years we have graduated two Ph.D. students. A third is expected to graduate by the end of this year. A fourth has just completed the necessary data acquisition for his thesis.

From the outset, our group has been widely recognized for our studies of the structure of bound nuclear states. The interplay between an active theory program and inelastic electron scattering experiments conducted at the Bates linear accelerator, with what is still the best resolution ever achieved at any laboratory, has produced results which have set the standard for the field. Our nuclear fitting codes have been the principal tool for extracting charge, current, and magnetization densities from inelastic electron scattering data, not only at our laboratory but at others as well.

As time has progressed and our group has expanded, so, too, have our interests grown and evolved. We pioneered the use of solid state detectors and avalanche counters in the environment of an electron beam at the superconducting accelerator at Stanford. When the high duty factor electron microtron, MAMI-A, was commissioned in Mainz, West Germany, we proposed a series of coincidence measurements of nuclear structure effects in the giant resonance region, using our expertise to develop the neces-

sary hardware. With little change in the initial design, this internationally recognized program has produced data of unparalleled quality.

Our initial interest in coincidence measurements, and our experience with the requisite techniques, has subsequently led us into studies of the general reaction mechanisms in the continuum region extending from the giant resonances, through the quasielastic peak, and into the area of the Delta-resonance. When the first studies of the dip region, between the quasielastic peak and the Delta, were initiated at Bates, our expertise was solicited to develop the coincidence logic. The program has been a great success. Our involvement with this work has continued with coincidence studies of the quasielastic and Delta regions both at Bates and at NIKHEF-K in Amsterdam.

We were the first group to propose triple coincidence measurements to unravel the reaction mechanism in the dip region. Our proposal to NIKHEF-K was accepted, stimulated the development of two large acceptance hadron detectors, in which we participated, and resulted in the first observations of an $(e, e'2p)$ cross section. We are presently preparing for the final measurements which will provide the first quantitative direct look at two-nucleon correlations in nuclei. These results will be crucial for the planning for all similar future experiments at the new high duty factor facilities being developed at Bates and at CEBAF, the Continuous Electron Beam Accelerator Facility, in Newport News.

Now our group is at a critical stage in its development. It is clear that the future of electromagnetic nuclear physics will revolve around experiments at the new facilities at Bates and CEBAF, just mentioned, and at Mainz, where an upgrade to 840 MeV is in progress. It is also clear that direct involvement in this future requires taking a major responsibility for the development of both hardware and software for data acquisition at these facilities. Those groups that take such a responsibility will participate in these future experiments, and those that do not will not. We have every intention of participating to the fullest extent possible.

Most recently, we have taken the leadership in proposing and providing the initial design for a large acceptance spectrometer, BLAST, for the upgraded Bates accelerator. We have also committed ourselves to major development projects for the CEBAF spectrometers.

In order to meet these challenges, during the past two years, we have built up, with support from the University, a detector development laboratory for the design, construction, and testing of prototype scintillators, Čerenkov counters, and wire chambers. This will provide our group with an in-house capability to do some hardware research and development, and we plan that our present and future personnel will all spend part of their time on this project. This will allow us to refine detector designs

prior to the large scale construction stage and provide our students with training and experience in the operation and use of various types of detectors.

It is clear, however, when one considers the size of the large acceptance spectrometers being designed for Bates and CEBAF, that a major construction effort is required to produce any significant component of the necessary hardware. Such a project is beyond the scope of this present proposal. In order to fund such a major new initiative, we will submit a second proposal which will request additional manpower as well as the necessary capital equipment and supplies. We mention this here in order to clarify our overall program now and in the future.

At the same time, it is absolutely essential that we maintain important parts of our present program while we prepare to use these future facilities. Although we are clearly dedicated to using the new facilities, they will not be operational until the third year of this present proposal, at the very earliest. Thus, while we must begin to develop the necessary detectors for our future program because that will require in excess of three years, we must also continue an active program of physics experimentation and analysis to provide thesis projects for our students and publishable work for our postdoctoral scientists. Furthermore, the present program has produced many interesting insights into nuclear structure and reaction mechanisms and promises to provide even more in the future. The continuation of various phases of the ongoing program and its relation to our future work is the purpose of this present proposal.

This proposal requests a continuation of our present level of personnel with a modest increase in the number of graduate students to between five and six by the third year. This will allow the continuation of most of the ongoing program as well as provide sufficient personnel to begin the detector development work outlined above.

In the following sections, we review the progress made during the past three years and outline our future plans for each of the three major experimental efforts in which we are active, (1) coincidence studies of giant resonances (Section B), (2) coincidence studies of reaction mechanisms and two-nucleon correlations in the deep inelastic region (Section C), and (3) inclusive scattering studies of bound nuclear states (Section D). We also review our progress in nuclear modeling. The non-relativistic shell model and core polarization calculations are discussed in Section D and in Section E we discuss our work with relativistic field theory models.

Section B

GIANT RESONANCE STUDIES

Seven years ago, we embarked on a program of coincidence $(e, e'x)$ studies of the giant resonance (GR) region of selected nuclei, in particular using $(e, e'p)$ and $(e, e'\alpha)$ reactions. The goals of this program were manyfold. First, we wanted to more fully investigate the properties of the giant dipole resonance (GDR) by studying its decay characteristics in as many outgoing channels as possible, as opposed to most real photon work which is limited to ground state transitions. Second, we wanted to make the first high precision measurements of *E2* strength in light to medium nuclei. Third, we wanted to initiate a systematic study of all GR's of all spins and parities in the p-shell nuclei ^{12}C and ^{16}O, varying both momentum transfer, q, and energy transfer, ω, while observing the various decay channels. Finally, we wanted to vary the incident electron helicity to determine the spin-dependent nuclear response in the GR region.

This program has been an active and integral part of the overall nuclear physics efforts since its inception, and has been particularly active during the past three years. Some of the goals outlined above have been met. Others await future work. The first phase of the program consisting of studies of ^{12}C, ^{16}O, and ^{40}Ca with $q \leq 0.6\,\mathrm{fm}^{-1}$, using the Mainz microtron, MAMI-A, is in the final analysis stages following the shutdown of MAMI-A in September 1987 for an energy upgrade. This phase of the program has been aimed at studying the GDR and isoscaler giant quadrupole resonance (GQ$_0$R). The ability to make measurements with a well understood probe, the electron, and to independently vary the experimental parameters of q, ω, and outgoing channel, p_i (or α_i), provides information that was heretofore unavailable from either real photon studies (both capture and photoreactions) or inclusive electron scattering, and that information is yielding a new insight into the structure of resonances previously thought to be well understood. While several properties which we have observed in the *E1* GDR are as expected on the basis of real photon work, there are a number of differences which were observed for the first time.

In the meantime, first data were obtained using the Bates linear accelerator at the highest q observed at Mainz. The results agreed very well, providing a "proof

of principle" that such experiments can in fact be carried out in the low duty-factor environment provided that the peak current is maintained to be at or near that of MAMI-A. More recently, we have just completed the first measurements at Bates at higher q than reached at Mainz. In addition, we have a proposal that was approved by the Bates PAC in 1986 to make the first measurements with polarized electrons, and we anticipate that this will run within a year (after the Wien filter is installed on the polarized source to allow maximum beam polarization on target at all energies). Finally, we had a proposal approved by the most recent Bates PAC to extend these measurements to $q \sim 2\,\mathrm{fm}^{-1}$ using the South Hall Ring (SHR), to be completed at Bates in 1993. The Bates SHR will provide a unique facility with which to pursue these studies, providing polarized electrons at high energy and high duty factor.

Thus we have completed the first phase of our experimental program and are embarked upon the second. The experiments at Mainz are finished. The remaining future of this program resides at Bates. Now that we have successfully shown that these experiments can be performed at Bates, we are poised to fulfill the last two goals outlined earlier. We summarize the Mainz results, discuss the present status, and outline our future plans to finish the analysis and publish the results in sections B.1 through B.4. We describe the recent program at Bates and our future schedule including the first experiments with the SHR in sections B.5 and B.6. Additionally, there are two other items to discuss. One is to report the publication of some GR studies completed during the previous three years, on $^{238}\mathrm{U}(\alpha, \alpha' n)$ and $(\alpha, \alpha' f)$. The second, discussed in section B.7, describes some $^{12}\mathrm{C}(\gamma, p_1)$ and $^{16}\mathrm{O}(\gamma, p_3)$ studies that remain to be done. Finally, we summarize the equipment and manpower requirements to continue this program and its integration into our overall nuclear physics program in section B.8.

B.1 $^{12}\mathrm{C}(e, e'p)$ and $^{16}\mathrm{O}(e, e'p)$ at Mainz

The studies at Mainz have been aimed at making accurate measurements of the angular correlations for the charged particle decay from the giant resonance region to the various allowed open channels, for $q \leq 0.6\,\mathrm{fm}^{-1}$. From these correlations, the major lower order multipole contributions, *E1* and *E2* or *E0*, can be determined, and the *E1* can be separated into longitudinal and transverse components.

We have been analyzing the data by two different methods, which we will discuss in this section. However, we first, present some experimental observations, which can be made directly from the cross sections, independent of method of analysis:

(1). The decay of the GR region of $^{12}\mathrm{C}$ is dominated by the emission of protons leaving $^{11}\mathrm{B}$ in its $\frac{3}{2}^-$ ground state, *i.e.* $(e, e'p_0)$, with a $\sim$10-20% probability of $(e, e'p_1)$ to the $\frac{1}{2}^-$ first excited state. There is even weaker decay (by another order of magnitude) to the unresolved (in our experiment) second and third excited states.

In $^{16}O(e, e'p)$, the decay is approximately evenly divided between the p_0 channel, leaving ^{15}N in its $\frac{1}{2}^-$ ground state, and p_3 decay to the $\frac{3}{2}^-$ third excited state near 6.0 MeV. There is a very weak branch to the unresolved positive parity doublet near 4.5 MeV.

This work represents the first direct measurements of the proton decay of the GR's in ^{12}C and ^{16}O to final states other than the ground states of the residual nuclei. For both $^{12}C(e, e'p)$ and $^{16}O(e, e'p)$, the distribution of final states in ^{11}B and ^{15}N, respectively, is quite similar to the missing mass distributions from quasielastic knockout (QES);[1,2] and are known to be mainly proton hole states in the $1p$-shell. This similarity strongly suggests that direct and semi-direct (*i.e.*, direct doorway decay) processes are dominant. Final states requiring multistep processes characteristic of equilibrium and pre-equilibrium decay are only weakly excited if at all.

(2). In the range of q spanned by our experiments at Mainz, 0.24 – 0.60 fm^{-1}, as expected, the reaction proceeds predominantly through the absorption of *E1* virtual photons, at least for $(e, e'p_0)$, resulting in excitation functions *vs.* ω very similar to those for $^{12}C(\gamma, p_0)$ and $^{16}O(\gamma, p_0)$, and angular correlations characteristic of *E1* radiation, with maxima near $\theta_p = 0°$ and 180° (parallel and anti-parallel to q) and a *single* minimum near 90°.

(3). The strong maximum in the excitation function, similar to that for (γ, p_0), clearly indicates that the reaction mechanism is predominantly resonant, *i.e.*, the reaction proceeds through the formation and decay of well defined intermediate doorway states. This coupled with observation (1) above provides strong evidence that we can describe the reactions using a semi-direct mechanism.

Now, we proceed to describe the analysis. The angular correlations can be analyzed independently for each decay channel. These correlations must be of the general form[3,4,5]

$$\frac{d^5\sigma}{d\omega d\Omega_e d\Omega_x} = \frac{d^3\sigma}{d\omega d\Omega_e}\Bigg(\sum_k A_k P_k(\cos\theta) + \sum_k B_k P_k^1(\cos\theta)\cos\varphi + \sum_k C_k P_k^2(\cos\theta)\cos 2\varphi\Bigg),$$

where θ and φ are the polar and azimuthal angles of particle x with respect to the direction of q, and the sums run from 0, 1, and 2, respectively, up to twice the highest contributing multipolarity. In a pure resonance approximation, the coefficients A_k, B_k, and C_k are proportional to products of form factors and decay amplitudes.

All our data from the Mainz work were taken at fixed φ=135°, which eliminates (except for geometrical acceptance effects) the third sum. Since *E1* is the dominant

multipole for our kinematics, and if we further assume that the GDR consists of a *single* collective configuration, as was done by Kleppinger and Walecka[4] in their Static Limit Resonance Approximation (SLRA), the coefficients A_0, A_2, and B_2 are unique functions of C1 and T1, the longitudinal and transverse form factors for $(e, e'x)$ to the particular channel under analysis, and a_2, the coefficient of the $P_2(\cos\theta)$ term at $q = \omega$.

Similar relationships can be written down for *E0*, *E2*, etc., and for the terms arising from the interference of all contributing multipoles. We have fit the angular correlations using the full expression, allowing the *E1* to be fit first and then including the other multipoles up to *E2*. Such a fit, then, yields an experimental determination of C1, T1, and a_2, and the strength of interfering multipoles. Furthermore, the relative sign between C1 and T1 is determined. Here we summarize the results for $^{12}C(e, e'p_0)$ and $^{16}O(e, e'p_0)$ based on this analysis and discuss some of its shortcomings and their resolution.

(4). In $^{12}C(e, e'p_0)$, the *E1* strength is dominant, as expected, throughout the region between E_x = 20 and 28 MeV. There is, however, significant *E0* strength between 18 and 22 MeV (centered at about 19.5 MeV) in agreement with the earlier work of Calarco, *et al.*[6] There is also a significant amount of *E2* strength which extends from about 24 MeV to > 28 MeV. At our highest $q = 0.59$ fm^{-1} this strength is $\sim$ 25% of the *E1* around 26–28 MeV. However, it is clear that no other multipole contribution is as large as or larger than the *E1* in the kinematic range studied in our work.

In $^{16}O(e, e'p_0)$, the cross section is predominantly *E1* with an *E2* contribution which rises from near zero at 23 MeV and increases with energy. For the lower energy region, near 22.3 MeV, the correlations display the behavior expected for dominant *E1* radiation. There is a forward-backward asymmetry which increases with q, indicative of increasing interference from a multipole of opposite parity (most likely *E2*). For the higher energy region near 24.5 MeV, there is strong interference even at low q, and this gets even stronger with increasing q. At the highest q studied (0.6 fm^{-1}) the *E1* and *E2* cross sections are essentially equal near 28 MeV. Thus the qualitative behavior is similar to that for ^{12}C, but there appears to be $\sim 3-4$ times more *E2* strength in ^{16}O than in ^{12}C. There remains a question concerning the absolute normalization of this strength. A Letter has been drafted and will be submitted as soon as this last question is resolved.

(5). The *E1* strength is predominantly longitudinal, again as expected in our regime of kinematics (θ=22°–40°and low q).

(6). For both ^{12}C and $^{16}O(e, e'p_0)$, the total *E1* form factor is consistent with that calculated from the Tassie model for a transition radius of $\sim$ 1.2 times the ground state radius. A similar inflation of the transition radius was observed in the analysis

of highly excited states in $^{16}O(e,e')$ data from Bates[7] However, this q-dependence is inconsistent with inclusive $^{12}C(e,e')$ results in the same range of q and with earlier work on $^{16}O(e,e')$, which concentrated on *E1*/*E2* separations, both of which are generally consistent with a transition radius equal to that of the ground state. The more recent Bates $^{16}O(e,e')$ work was concentrated on higher spin states.

(7). If the Tassie fit with $r_{tr} = 1.2\,r_{gs}$ is correct, then the *E1* strength for $^{12}C(e,e'p_0)$ exhausts $\sim$ 20% of the TRK sum rule, consistent with that expected on the basis of photonuclear data[8,9,10,11] from which it is known that the GDR strength up to 28 MeV only exhausts $\sim$ 45% of the sum rule with about half of that going to the neutron channels.

In $^{16}O(e,e'p_0)$, the *E1* strength appears to exhaust about 15% of the sum rule. This is somewhat small ($\sim 60 - 75\%$) compared with values from photonuclear measurements. It is this discrepancy which has raised the question of scale normalization discussed earlier in regards to the *E2* strength.

In both cases, forcing a fit to the form factor with $r_{tr} = r_{gs}$ yields an integrated strength which is unexplainably below the fraction of the sum rule seen at the real photon limit. A large amount of time was spent at Mainz checking the normalizations. As yet, no major (or minor) errors have been found. There is no evidence for a strong q-dependence to the fraction of decay of the GDR to the proton channels since the relative population of $(e,e'p_0)/(e,e'p_3)$, *etc.*, remains approximately constant. The most likely reason for this discrepancy is that inclusive (e,e') results for the GDR include a contribution from an incompletely subtracted background, such as radiative tail, or contamination from higher multipoles such as *E2*. The latter effect would certainly result in the form factors being too large at higher q, which, if neglected, could be interpreted as evidence for a smaller transition radius.

(8). These results were obtained within the constraints of the SLRA; the value of a_2 should be independent of q and was fixed to that for the real photon data throughout the GDR region. Relaxing this constraint, and allowing the value of a_2 to be free, results in an improvement in χ^2 by about a factor of 2, and in a value of a_2 with a q-dependence, becoming approximately 20-25% more negative than the photonuclear value at $0.6\,\mathrm{fm}^{-1}$. However, the best fit values of C1 and T1 are not changed significantly. This indicates that either the SLRA is only approximately valid and that direct processes are important although not dominant, or that we are not including some contributing amplitudes in the fit. Both are probably true to some extent.

The major new finding concerns the q-dependence of our fitted T1, which is almost entirely determined by the value of the angular coefficient B_2 which arises from the "third" response function, due to longitudinal/transverse interference, which is not

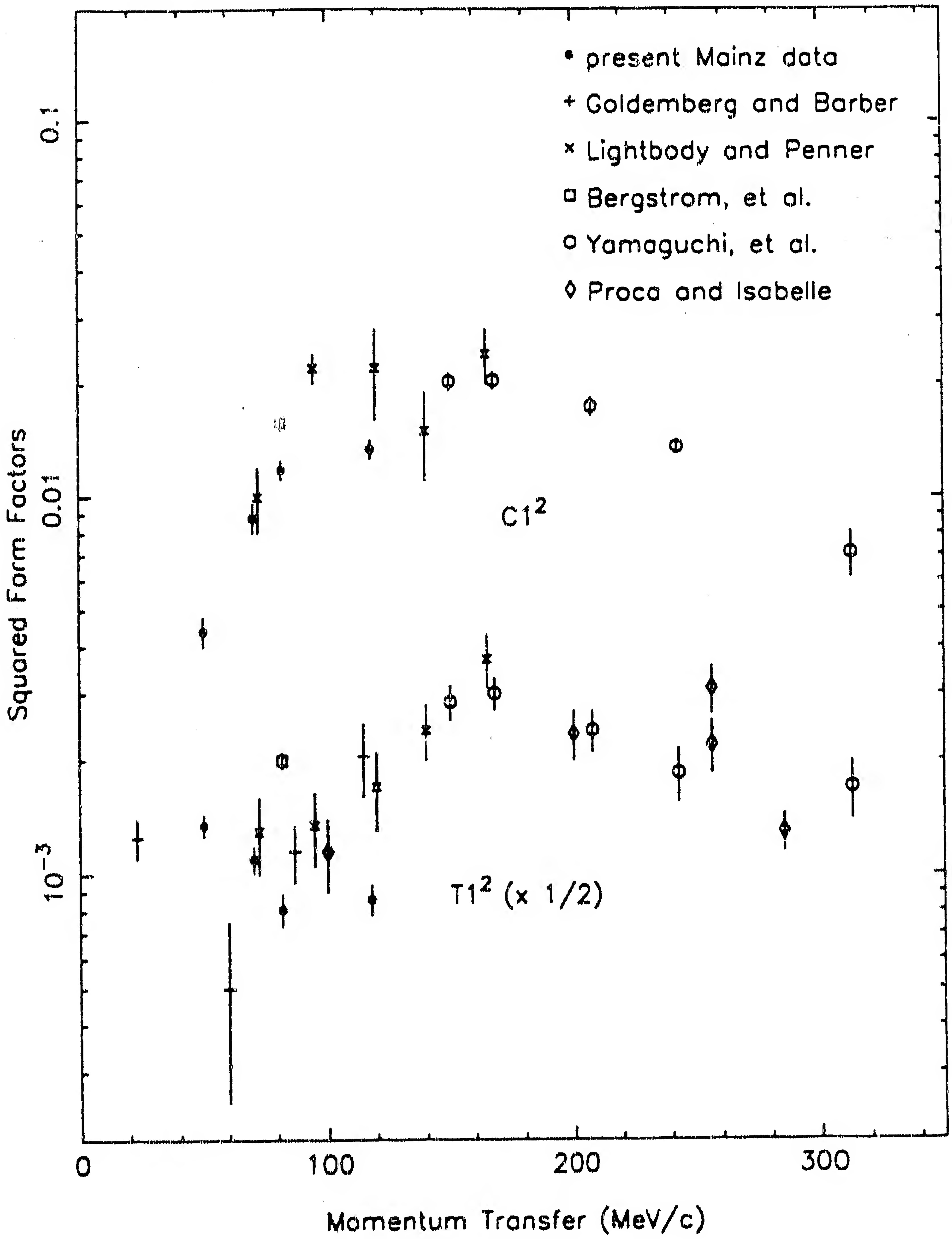

Fig. B.1 A comparison of longitudinal and transverse form factors for $^{12}C(e, e')$, as extracted from inclusive (e, e'), with those from the present work where the transverse is primarily determined by the third response function.

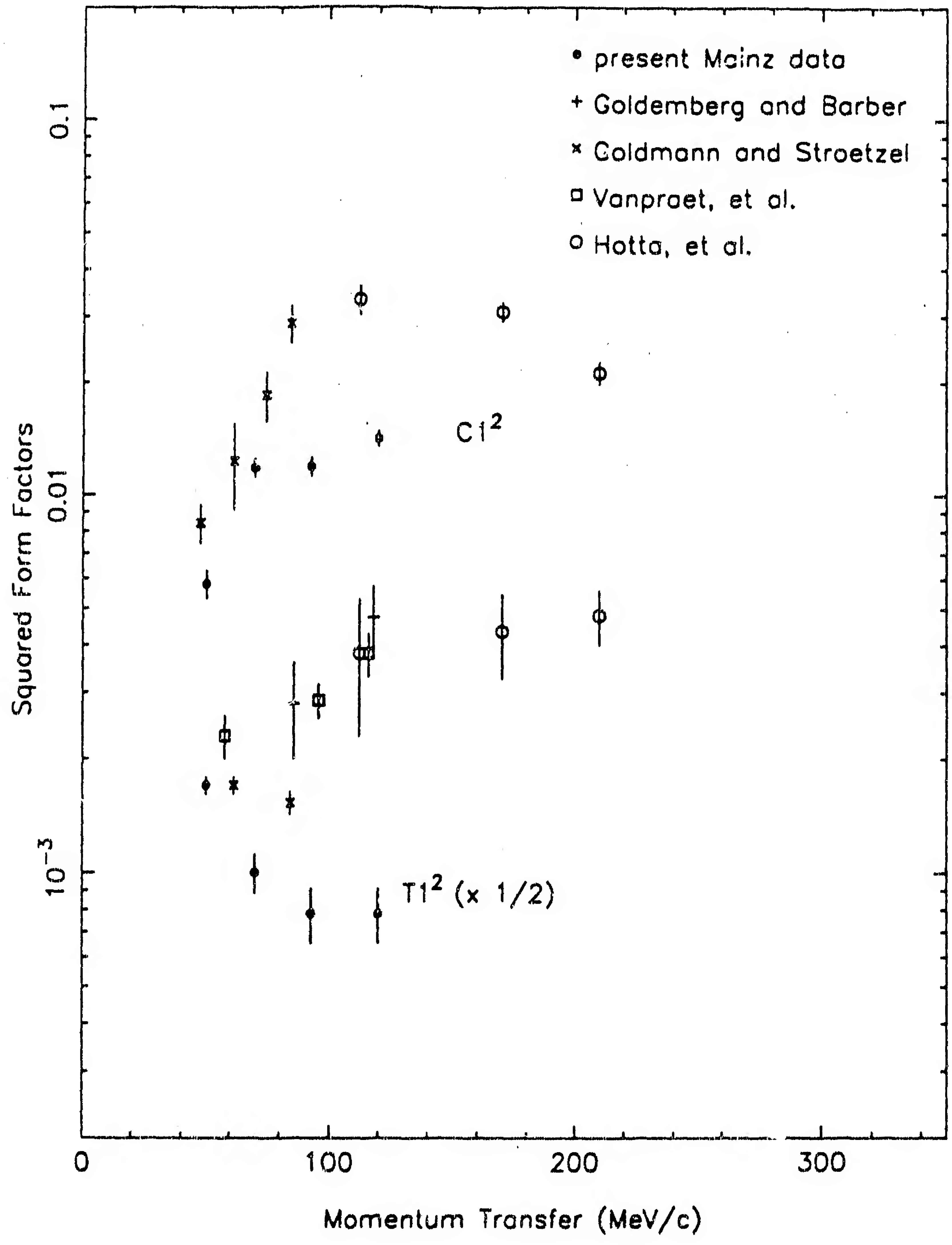

Fig. B.2 Same as the previous figure, but for $^{16}O(e, e')$.

observable with either real photon experiments or inclusive (e, e'). At low q, the ratio T1/C1 is approximately consistent with Siegert's theorem in both magnitude and relative phase, although the magnitude is a little high (by ~20%). However, as q increases, the best fit T1 decreases rapidly, still in agreement with Siegert's theorem, but in total disagreement with results from inclusive 180° scattering[12] and Rosenbluth separations,[13,14,15,16,17] all of which find T1 rising with q between 0.3 and 0.6 fm^{-1}, pointing to a second dipole state with a rapidly rising transverse amplitude, as shown in Figs. B.1and B.2.

This is not due to any artifact of the analysis procedure. An inspection of the angular correlations (see Fig. B.3.) clearly indicates that there is a significant deviation of the axis of symmetry from along q at 0.24 fm^{-1}, which then is reduced at 0.6 fm^{-1}. This deviation is a measure of the magnitude of the coefficient of the P_2^1 polynomial and a clear signature of the third response function. It is definitely decreasing in relative significance with increasing q.

This indicates a failure of the SLRA as applied to the analysis insofar as it includes only a *single* resonance which is constrained to be the same at the real photon point.

The SLRA formalism itself allows for an arbitrary number of interfering amplitudes of the same or different spins and parities. Much effort was made during the past two years to incorporate multiple dipole resonances into the analysis. The analytic work is straight forward and complete. The results yield a much more complicated set of relations between the coefficients A_k, *etc.*, and the parameters $\mathrm{C1}_i$, $\mathrm{T1}_i$, and $a_2(i)$ for the component resonances. It is clear that this prevents a model independent fit of C1 and T1 because of the large number of free parameters. It is also clear, however, that even in the simplest case of a single collective state interfering with a single spin-flip state (which has a purely transverse response), the value of T1 determined in the SLRA must be interpreted as a *coherent* sum of the two transverse responses, and the value of a_2 becomes some weighted average with a q-dependence. Then the simple expressions for A_0, A_2, and B_2, based upon the *single* resonance assumption, yield *effective* amplitudes T1 and C1, which are coherent combinations of contributions from the allowed doorways. In order to investigate this, we have calculated the expected inclusive and exclusive results from a simple model using two extreme pictures of the doorways.

Let us assume that two *E1* doorways contribute (there may be more): a collective GDR and a spin–flip GR. We have obtained the L and T photon absorption amplitudes for these doorways from (1) the generalized Goldhaber-Teller model (GGT) as described by Überall[3] and (2) the 1p-1h Tamm-Dancoff calculations of Donnelly.[18] For each of these, we have used the p_0 decay amplitudes calculated by Mavis.[19] In the doorway

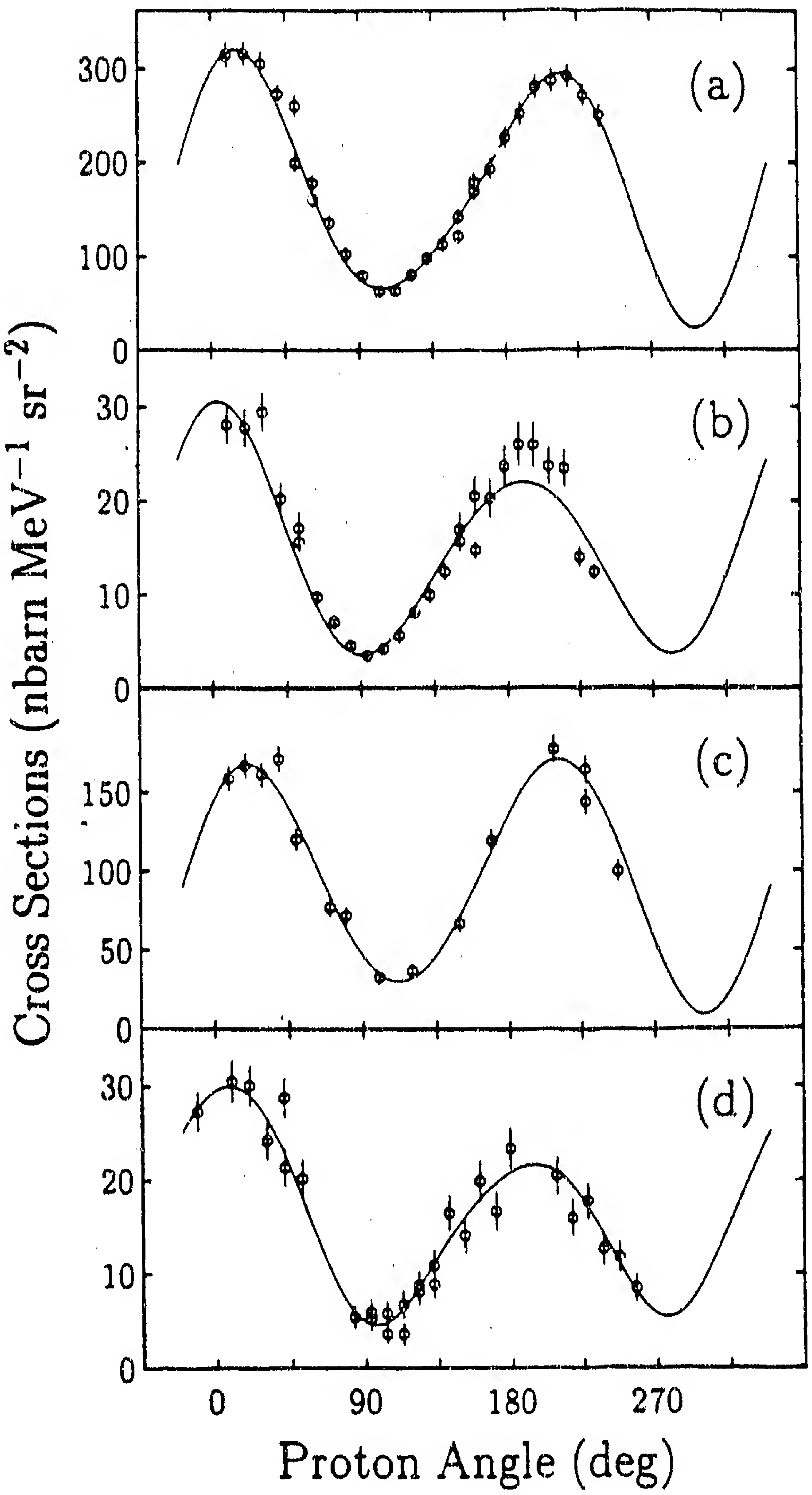

Fig. B.3 A comparison of angular correlations for $^{12}C(e, e'p_0)$ at 0.24 fm^{-1} (a) and 0.6 fm^{-1} (b) and for $^{16}O(e, e'p_0)$ also at 0.24 (c) and 0.6 fm^{-1}(d). Note the decreasing shift away from 0° with increasing q.

model, the total reaction amplitudes are simple products of these absorption and decay amplitudes.

In this simple model, the collective GDR contributes longitudinal and transverse amplitudes $C1_A$ and $T1_A$ while the spin–flip GR contributes only a transverse amplitude $T1_B$. In the low q limit $T1_A$ and $T1_B$ are of opposite sign as are $C1_A$ and $T1_A$.

We have then inserted our calculated longitudinal and transverse reaction amplitudes into the Kleppinger and Walecka[4] formalism to yield the Legendre coefficients A_0, A_2, and B_2 and the inclusive $|T1|^2_{incl}$. From the Legendre coefficients, we then calculate the effective C1 and T1 which would be obtained had we assumed only a *single* resonance.

The result of this calculation is that while the inclusive results are still given by $|T1|^2_{incl} = |T1_A|^2 + |T1_B|^2$, the exclusive analysis is sensitive to:

$$a_2(C1)(T1) = C1_A[a_2(A)T1_A + Re\{a_2(A,B)T1_B\}]$$

where $a_2(A,B)$ is a complex function of products of decay amplitudes from the two resonances. Since $|T1|^2$ is small compared to $|C1|^2$, the effect of this is on $|C1|^2$ is small while that on $|T1|^2$ is very large. In fact, the effective $|T1|^2$ is predicted to decrease with increasing q as observed in the data analysis. The calculations using both the GGT and 1p-1h models are qualitatively consistent with the trend of the experimental results. No attempt has been made to change or optimize input parameters. In order to check the consistency of this model, we are presently refitting the data directly with a general set of Legendre coefficients which we can compare directly to calculation.

Thus, our principal conclusions are: Since the effect on $|C1|^2$ is small, most of any discrepancy between the inclusive and exclusive determinations of $|C1|^2$ is due to background contaminations and higher multipole contributions in the inclusive results. However, the exclusive results on $|T1|^2$ clearly display the sensitivity of this measurement to interfering transverse amplitudes and provide unambiguous evidence that there is at least one interfering amplitude. Furthermore, since the effect is primarily on $|T1|^2$, the interfering doorway has a negligible C1 contribution and is thus the predicted spin–flip resonance.

A real surprise from the $^{16}O(e,e'p)$ data came when we tried to analyze the cross sections and angular correlations for the $(e,e'p_3)$ channel. We continue our summary:

(9). The p_3 cross section exhibits considerable structure. There are four points worth noting. First, the relative strength of the various structure peaks is clearly dependent on q. Second, the excitation energy of the various peaks lines up reasonably well with corresponding structure in the p_0 channel. Third, the angular distributions clearly

exhibit a strong dependence on both excitation energy and q. Finally, although we have not yet been able to analyze these in detail, we can say that, since the distributions have only one minimum in 180°, they are consistent with an *E1* dominated cross section.

When compared with the results on $(e, e'p_0)$, these various observations appear to be in conflict. In $^{16}O(e, e'p)$, both the p_0 and p_3 channels are expected, *and observed as noted earlier*, to be strongly excited in the decay of the GDR since both are $1p$-hole states (in fact, dipole matrix elements and level populations both favor dipole decay via p_3 emission). Thus, if the p_0 channel exhibits the rather uniform behavior, with excitation energy, of the form factors and angular coefficients, as expected from a dominant collective dipole mechanism, it is rather surprising that the p_3 channel doesn't. If dipole decay does dominate the p_3 channel, then the difference in q-dependence of the various peaks in the cross section, and their corresponding angular correlations, clearly means that there is a significant variation in the dipole form factors associated with these structures, something which is not seen in the p_0 channel.

(10). Finally, the characteristics of the $^{16}O(e, e'p_3)$ and $^{12}C(e, e'p_0)$ cross sections are expected to be very similar on the basis of microscopic 1p-1h descriptions of the GDR's in these two nuclei; both reactions are expected to proceed via proton emission leaving the residual nucleus with a hole in the $p_{\frac{3}{2}}$ shell. Indeed, some calculations[19] show them to be almost identical. Our observations are clearly at odds with this expectation. Not only does the ^{12}C decay *not* exhibit this variation, *but* a direct comparison of the angular correlations and the corresponding coefficients shows them to be much different. This is shown in Fig. B.4.

To summarize the tasks remaining to complete this project, the primary job is the resolution of the apparent problem regarding the normalizations of the higher q points. This impacts principally on the absolute magnitude of the *E2* strength and to a lesser extent on the interpretation of the dipole transition radius. Nevertheless, even at this stage, we conclude that we see some interesting physics not normally associated with GR's, *i.e.* either dipole states with bizarre q-dependence or other multipoles with surprisingly large strength. More importantly, we have directly observed the interference of the collective GDR with the spin-flip GR.

Three *Phys. Rev. Letters* are already in draft form. One, on the ^{16}O *E2* strength, is pending resolution of the normalization question. The second, on the two-state interference model for the effective T1, is essentially complete. We must complete and check calculations on the ^{16}O p-h model and make figures. We must also complete our generalized Legendre analysis. The third, on the $^{16}O(e, e'p_3)$ and $^{12}C(e, e'p_0)$ comparison, is also essentially complete; one of our collaborators, Milan Potokar of the Institute Jošef Stefan in Ljubljana, Yugoslavia, is making some semi-direct model calculations on this.

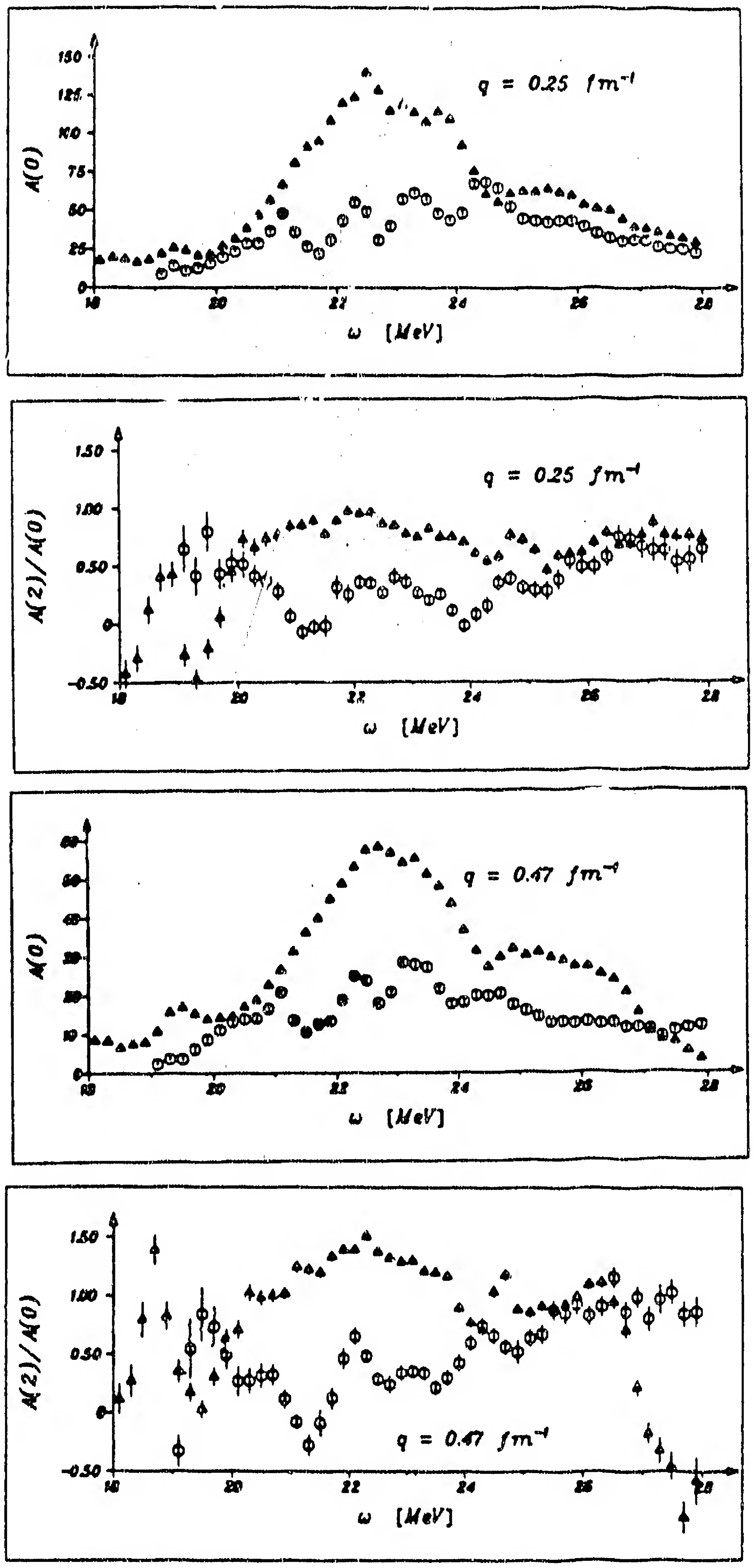

Fig. B.4 A comparison of the A_0 and A_2 coefficients for ^{12}C (triangles) and ^{16}O (circles) at two values of q.

We have also started to draft two larger *Phys. Rev. C* articles describing the details of the ^{12}C and ^{16}O experiments and results.

These remaining tasks and the preparation of the results for publication are the responsibility of one faculty member, John Calarco. It is anticipated that this work will be complete, except for manuscript revisions, by the summer of 1991. Aside from publication costs, no additional resources are requested to complete these studies. No additional graduate students will be assigned to this project.

B.2 ^{12}C$(e,e'\alpha)$ and ^{16}O$(e,e'\alpha)$ at Mainz

In addition to studying the proton decay from the GR region, we are in the process of extracting ^{12}C$(e,e'\alpha)$ cross sections for the excitation region of 18–28 MeV. For much of this region, separation of the α_0 and α_1 channels is difficult because the final states in ^{8}Be are broad and only separated by 2 MeV. However, we are presently working to make a separation in selected regions where the cross sections and, thus, the statistical accuracy of the data allow it.

The summed $(e,e'\alpha)$ cross sections are dominated by a strong resonance near 21.5 MeV with additional structure at around 18 and 24 MeV. The resonance is undoubtedly that tabulated by Ajzenberg-Selove[20] at 21.60±0.10 MeV with a width $\Gamma = 1.2$ MeV. This level is seen in several reactions and is known to decay into the α channel (as well as others, including γ). However, different reactions appear to assign a different spin and parity to this level, leading Ajzenberg-Selove to suggest an unresolved pair of states with $J^\pi = 3^-$ and 2^+. The isospin is not assigned.

For the summed α_0 and α_1 decays, we fit the angular correlations with the *single* resonance SLRA formalism throughout the excitation region of 18 to 28 MeV, assuming an admixture of C2, T2, and C3 form factors. As in the $(e,e'p)$ analysis, this procedure yields effective amplitudes if there is more than one resonance for *each* spin and parity. In the case of narrow structures, as we see here, however, it should be adequate. In the region of the resonance at 21.5 MeV, the fits indicate a small but non-zero amount of *E3* strength dominated by *E2*. However, it will be interesting to fit the data at higher q, because the integrated cross sections clearly indicate that this resonance is growing more rapidly with q than the remaining cross section, suggestive of a growing *E3* contribution. This is part of the program of analysis we plan to do this year. In fact, we have determined that this is one region of excitation energy where it appears that we will be able to separate α_0 and α_1 with confidence, and we are presently working on this problem.

Up until now, we have been plagued with a normalization problem when overlapping different regions of the angular correlation. This has led to ambiguities in

the fitting results. In order to resolve this, we are presently implementing the Mainz data reduction code EUMEL on our VAX system. This will allow us to test whether the problems are associated with tape reading errors. It will also streamline the data reduction by incorporating improved graphics in the software cutting procedures.

In the meantime, a student from Mainz, Johannes-Peter Fritsch, has been analyzing the $^{16}O(e, e'\alpha)$ data at Mainz and has completed a first set of fits. Like the $^{12}C(e, e'\alpha)$, the cross sections exhibit considerable structure; strong resonances are observed in both the α_0 and α_1 decay channels near 18.5 and 20.6 MeV. (Unlike the case of $^{12}C(e, e'\alpha)$, there is no difficulty separating α_0 and α_1 due to the 4.4 MeV final state energy difference.) These resonances have been reported before[20] and are assigned a spin and parity of 2^+. However, the preliminary SLRA fits show that there is certainly some *E0* and possibly some *E3* strength in the same region.

When these two analyses are complete, we expect the results to be published in two separate papers. We anticipate the first, on ^{16}O to be written during early 1991. The second, on ^{12}C, may be delayed depending on the Bates results.

The $^{12}C(e, e'\alpha)$ project is the principle responsibility of one of our present students, Dave DeAngelis. It will be combined with studies of the same reaction at higher q at Bates (see section B.5.) as part of his Ph.D thesis work. The only additional resource needed to complete this project is an Atari graphics terminal (or equivalent) to facilitate the operation of EUMEL.

B.3 $^6Li(e, e'p)$ and $(e, e'\alpha)$ at Mainz

In the course of obtaining data on $^{16}O(e, e'x)$ using targets of $^6Li_2O$, we have also obtained a complete set of data on $^6Li(e, e'x)$ as a dividend. The primary reason for the choice of this target material for the ^{16}O studies was that it provides a thin, self-supporting, non-extended oxygen target in which all contaminants are kinematically resolvable. Thus, we also have cleanly resolved the reaction products from both $^6Li(e, e'p)$ and $^6Li(e, e'\alpha)$.

The $^6Li(e, e'p)$ data are being analyzed by a Mainz student, Andreas Grasmück, as part of a Master's thesis project. The results from a first analysis are complete, and we expect to publish the final results within a year.

Protons are observed in the ^6Li decay leaving ^5He in its unbound ground and first excited states. The ground state reaction, $^6Li(e, e'p_0)$, has been analyzed. The process appears to be consistent with direct knockout; there is no resonant structure in the excitation function, and the proton angular correlation is extremely forward peaked. Thus far, these correlations have been fit only with an analytical function which is

essentially a modified Gaussian peaked at $\theta_p=0^\circ$ (along q). From this fit we will extract a parameter which describes the ground state momentum distribution in ^{6}Li.

We also plan to fit the data with a general Legendre fit to see if any additional information or insight can be gained from systematics of the fitted coefficients. We expect that, since we are constrained to low q, only multipoles up to *E2* and possibly *E3* will contribute significantly and that the very forward peaked angular correlations can also be fit with approximately equal *E1* and *E2* contributions. However, these fits have not been made yet.

The Legendre fits will be made at UNH using our codes. This will require a small fraction of the time of one student. It should be possible to fit the cross sections in about two weeks to a month, allowing time to vary different sets of parameters.

The $^6\mathrm{Li}(e,e'\alpha)$ cross sections have not yet been extracted from the event data. We plan to take a look at this at UNH to see if it is possible to extract reliable cross sections. The primary problem is that there is a very large forward/backward kinematic shift of the outgoing α's due to the center-of-mass motion of the recoiling ^{6}Li. For the backward α's, this presents a possible problem due to detection thresholds.

An initial investigation of the $(e,e'\alpha)$ problems will take a small fraction of the time of this same student. This will be a new student who will spend a significant fraction of time on another project, such as the $^{40}\mathrm{Ca}(e,e'x)$ analysis described in the following section, as well as detector development.

B.4 $^{40}\mathrm{Ca}(e,e'p)$ and $(e,e'\alpha)$ from Mainz

We have been asked by our collaborators at Mainz to complete the analysis of the data for the reactions $^{40}\mathrm{Ca}(e,e'p)$ and $^{40}\mathrm{Ca}(e,e'\alpha)$, which were taken a few years ago. These data were partially analyzed by a student at Mainz who subsequently had to leave before completing the project, and there is no other new student on this project.

The quality of these data are quite good. The reactions were measured at three values of q from 0.24 to 0.60 fm^{-1}. Protons leaving ^{39}K in its ground state are cleanly resolved. The excited states are not resolved except in groups of three or four. However, the complete continuum of protons above the Coulomb barrier threshold is observed. The alpha decay channels to the low-lying final states in ^{36}Ar are resolved.

The data at the two higher q values have been reduced to cross sections. The data at the lowest q have not been analyzed at all. None of the angular correlations have been fit with any model.

The interest in these data is twofold. First, ^{40}Ca is sufficiently large that the peak of the *E2* form factor is accessible at the highest q reached at Mainz. Second,

^{40}Ca is sufficiently complex that damping of the GR's is important, resulting in the "evaporation" of protons leaving the residual nucleus in highly excited states, as evident by the proton continuum observed in the experiment.

Because of the large $E2$ form factor, it will be interesting to fit the ground state angular correlations and search directly for $E2$ strength in the coefficient of the P_4 Legendre polynomial, rather than in the forward/backward asymmetry as in lighter nuclei. This $E2$ strength can then be compared with that from various other reactions on ^{40}Ca to determine branching ratios and isospin character.

Previously, evaporation decay spectra from GR's have been studied in the neutron channels from very heavy nuclei, where the evaporation process is dominant. Very little attention has been paid to evaporation of protons, primarily because charged particle decay is almost totally suppressed in these heavy nuclei. However, the disadvantage of studying heavy nuclei is that, except in special cases such as ^{208}Pb, decay channels to specific final states cannot be resolved. These data will allow us to study the evaporation to specific states with good statistics and resolution. ^{40}Ca is also interesting because the semi-direct process is not negligible ($\leq$10%) as in heavy nuclei, allowing the competition between these processes to be studied.

This project will constitute a Master's thesis for a new student whom we hope to attract to our group. This student will be expected to spend approximately half his or her time on this project while helping to develop detector hardware for future experiments at Bates and CEBAF. This dual responsibility will give the student the opportunity to learn as much as possible about performing nuclear physics experiments.

The additional resources requested to carry this project forward are the funds to support a graduate student. The EUMEL code and associated graphics terminal previously discussed in connection with the ^{12}C$(e, e'\alpha)$ analysis would be used for this project.

B.5 ^{12}C$(e, e'p)$ and $(e, e'\alpha)$ at Bates

While the experiments were being completed at Mainz, a program to continue the studies of the GR's at higher q and with polarized electrons was initiated at the Bates linear accelerator. It has always been the plan that such a transition would occur when the Mainz microtron MAMI-A was shutdown. The lower energy of MAMI-A (183 MeV) limited experiments to $q \leq 0.6\,\mathrm{fm}^{-1}$ without going to large scattering angles and excessively long running times. Bates, on the other hand, provides a beam energy up to 900 MeV, and this allows higher q's to be studied at a fixed forward scattering angle by simply raising the energy. In fact, for $q > 0.6\,\mathrm{fm}^{-1}$, running times are shorter at Bates despite the 1% duty factor, due to the combination of smaller scattering angle

and larger spectrometer acceptance. There are no plans to continue this program at Mainz using the new microtron MAMI-B despite the obvious advantages of combined high duty factor *and* high energy because their program is completely oriented towards experiments requiring multiple magnetic spectrometers, such as $(e, e'2p)$ and $(e, e'p\pi)$ at high q. Furthermore, the Bates SHR, once completed, will provide the same advantages.

Getting the program going at Bates has been difficult, but success has now been achieved. Shortly after our program was initiated at Mainz several years ago, a feasibility test using a telescope of SSB detectors in coincidence with the MEPS spectrometer showed that it was possible to do these experiments at Bates as well, despite the low duty factor; using a low peak current equivalent to that used at Mainz, time-of-flight spectra were obtained between scattered electrons and decay protons from ^{12}C with good timing resolution (~3 ns) and peak-to-background ratio (~2:1).

The Bates PAC enthusiastically endorsed the proposed program. Beam time was granted. With a generous supplement from DOE, we purchased sufficient SSB detectors and electronics to operate 8 telescopes of 4 detectors each, capable of stopping protons with energy up tp 22 MeV.

However, in the meantime, subsequent feasibility tests ran into repeated difficulties due to beam halo. Since these telescopes operate in vacuum only ~12 cm from a target of thickness between 1.0 and 5.0 mg/cm^2, any small amount of beam halo striking the target frame (~1000 mg/cm$_2$) is disastrous. In fact, no differences were discerned between empty target frames and those with targets.

Nevertheless, because of our initial test success, we persevered. The beam optics were studied, particularly in the region of the switchyard. Additional diagnostics were developed, including SLAC type halo monitors, SEM foils with various sized holes, and target beam position monitors of ZnS coated aluminum with various sized holes.

The perseverance eventually was rewarded with success. A test run in November, 1988 demonstrated that we could now tune the beam to reproduce or initial observation of coincidences with a good signal-to-background ratio. A full scale run was made in January, 1989, and data were obtained at the highest q attained at Mainz (0.6 fm^{-1}) and one higher value. Several difficulties were encountered during this run, particularly with the trigger electronics and on-line diagnostics. As a result, we redesigned both the hardware and software.

Still, the January run demonstrated "proof of principle". A partial angular correlation obtained at 210 MeV and 35° scattering angle (q=0.6 fm^{-1}) overlapped with the Mainz results well within errors. Data obtained at 320 MeV and 35° demonstrated that we could successfully push this program to higher q. Cross sections were measured and count rate estimates for future runs were refined.

We recently had our first real production run in May-June, 1990. The run was a qualified success. We obtained complete angular correlations, 13 independent angles spanning the interval of θ_p from 0° to 240°, all in a single plane rotated 135° from the scattering plane as in the geometry used for the Mainz measurements, for two higher values of q than reached at Mainz, $0.75\,\mathrm{fm}^{-1}$ and $0.95\,\mathrm{fm}^{-1}$. These, in accordance with our program plan, were obtained at a fixed forward angle for MEPS of 35.1° while varying the beam energy from 255 to 322 MeV. In addition, we simultaneously monitored elastic scattering from the target using OHIPS at 23° on the opposite side of the beam.

The analysis of these data will yield two Ph.D. theses. Dave DeAngelis of UNH will extract the $(e, e'\alpha)$ cross sections and combine the analysis of the resultant angular correlations with those from our earlier Mainz data to obtain a complete picture of the alpha decay from 0.24 to $0.95\,\mathrm{fm}^{-1}$. Gail Dodge from Stanford, our collaborators on this project, will analyze the proton channels, with particular emphasis on the third response function, which provided so much insight into the Mainz results, and on the region at higher excitation energy than the GDR where the isovector *E2* strength is thought to be concentrated.

The measurements were too recent to permit showing even preliminary results. From the on-line diagnostics we can say that, as expected, the angular correlations are forward peaked and that there is still a strong minimum near 90°. Thus even up to $0.95\,\mathrm{fm}^{-1}$, we are in a regime where the nuclear response in ^{12}C is dominated by the GDR with strong interference from *E2*. There is considerable cross section at excitation energies higher than the GDR region, which leads us to believe we will get a good measurement of *E2* strength in that region.

Thus, we have successfully completed the two measurements at higher q which we initially proposed to the PAC. We had also hoped to make the first measurements with polarized electrons at 207 MeV, but, because of assorted problems with the beam and the equipment, each of which took time to solve, we had insufficient time to pursue this. We will discuss the polarization measurement in more detail in the next section.

The next set of these measurements at higher q will be after completion of the Bates SHR, probably during the last year of this three year proposal. The Bates PAC has already approved 240 hours of running time to use the extracted beam from the SHR into the same scattering chamber we are presently using.

The hardware for the experimental setup is almost complete. During this most recent run, we still had to rely upon some other laboratories to loan certain pieces of equipment, particularly detector bias supplies. During the next three years, we propose to purchase sufficient supplies to make the experimental setup complete and our group

less reliant on other groups. We feel that this is essential. While some groups readily loaned the necessary equipment, others took considerable persuasion and cannot be relied upon for the next round of experiments. In addition, the experience of the past run clearly taught us that we need to purchase a sufficient pool of spare logic modules to maintain the experiment in case of failure. Lost channels in some ECL modules cost us time which might have been used for some polarized data. We propose to purchase some ECL modules each of the next three years to overcome this limitation.

Finally, we plan to attract new graduate students into this program. The approved time at Bates is definitely sufficient to supply a new student with the data necessary for a thesis. Furthermore, these measurements have been presented to the PAC as part of a program and enthusiastically received as such. Thus, we expect additional theses to result from this work. During this next three years, we will also be preparing for other classes of experiments, in particular multiparticle coincidence studies, using large acceptance detectors being designed for Bates (BLAST) and CEBAF (CLAS). We plan to take a major responsibility for design, development, and construction of significant pieces of the hardware for these two systems. Those graduate students, who work on the GR studies for thesis projects, will be expected to contribute time and effort in this hardware development as part of their training.

B.6 ^{12}C$(\vec{e}, e'x)$ at Bates

In the previous section, we mentioned that we had hoped to take some $(\vec{e}, e'x)$ data during the recent run, although the primary goal of completing the unpolarized high q studies for the two these was achieved. We still have 174 hours of PAC approved time to run the ^{12}C$(\vec{e}, e'x)$ experiment prior to the commissioning of the SHR. This experiment was also given a high priority during a PAC review of the Bates program in April, 1989, to decide on a limited set of key experiments to perform during the SHR construction.

Although we had hoped to get some data recently, the operation of the source has not yet been optimized for this experiment. At present, the source operates without a Wien filter, a set of crossed electric and magnetic fields allowing arbitrary orientation of the spin axis relative to the momentum, independent of the beam energy. The result is that, at present, there are only a few "magic energies" at which maximum helicity is observed on target, and these are not near our operating kinematics. If things had worked sufficiently quickly to attempt a first asymmetry measurement, we would have still needed twice the amount of time allocated to get equivalent statistics to those initially proposed.

The goal of this experiment is to measure the polarization asymmetry, the "fifth" response function, in the decay of the GDR. Like the third response function already

discussed in section $B.1$. in conjunction with the Mainz experiments, the fifth response is also generated by an interference between longitudinal and transverse amplitudes. Unlike the third response, the fifth is due to the imaginary part of that interference. Hence, it vanishes in the limit of a *single* GDR state, but is expected to be significant if there is interference between the longitudinal amplitude from one state with the transverse amplitude from another.

To the Legendre polynomial expansion shown earlier, the fifth response adds an additional series of the form $h \sum D_k P_k^1(cos\theta_x) sin(\phi)$, where h is the electron helicity on target. For an interference between two different dipole states, we expect to measure a non-zero D_2 coefficient. For the case of a collective GDR interfering with a spin-flip *E1* state of similar strength, separated by an energy interval comparable to their widths, we estimate $D_2/A_0 \sim 10\%$. We expect this to describe the situation near $q \sim 0.8\,\mathrm{fm}^{-1}$, where the GDR form factor is decreasing and that for the spin-flip state is on the rise. We have proposed to measure this to a relative accuracy of 30% (or 3% absolute).

During this past run, we had decided to attempt a measurement at $0.6\,\mathrm{fm}^{-1}$, a compromise imposed by the absence of the Wien filter. Even so, the maximum helicity on target was only expected to be $\sim$75% of that from the source. At higher energy and q, the helicity would have been even less.

We plan to obtain measurements with the Wien filter at two values of q to investigate the energy dependence of the D_2 coefficient. These measurements will be made before the SHR is completed. They will provide both a first look at this important parameter as well as a test of the method in preparation for further experiments with the SHR.

These measurements will constitute part of the thesis requirements of a new Ph.D. student. No additional hardware resources are requested. The SSB detector telescopes and associated electronics in hand and requested for the higher q experiments will fulfill the needs of the asymmetry measurements.

B.7 ^{12}C(γ, p_1) and ^{16}O(γ, p_3)

There is still one small experiment which needs to be completed before the Mainz measurements and future experiments can be fully interpreted. Analysis of the Mainz measurements has uncovered an ambiguity that can only be resolved by a measurement at the real photon limit.

Ambiguous sets of fits result from using the SLRA analysis because the Legendre coefficients are in the form of products of fitting parameters. For ^{12}C$(e, e'p_0)$ and ^{16}O$(e, e'p_0)$, the ambiguity is resolved because the value of a_2 at the photonuclear limit

is known; we can use this value as a starting point. For $^{12}C(e,e'p_1)$ and $^{16}O(e,e'p_3)$, no photonuclear data are available. Direct fits to the $^{12}C(e,e'p_1)$ and $^{16}O(e,e'p_3)$ cross sections yield equivalent fits (χ^2 equal to better than three significant figures) with very different sets of fitted coefficients.

For $^{12}C(e,e'p_1)$, one set includes an a_2 near -0.5 but with a dominant transverse amplitude. The other has a dominant longitudinal amplitude, which we would expect for excitation of the GDR at our kinematics, but an $a_2{\sim}{+0.2}$. A value of a_2 near 0.2 is not ruled out by any theoretical argument, but a value near -0.5 is expected on the basis of naive arguments based on partial wave composition of the outgoing proton wave function. This channel includes only two partial waves, $d_{\frac{3}{2}}$ and $s_{\frac{1}{2}}$. The $d_{\frac{3}{2}}$ is expected to dominate as in the $^{16}O(e,e'p_0)$ decay which also goes from a 1^- GDR to a $\frac{1}{2}^-$ final state and which is characterized by an $a_2{\sim}{-0.5}$. Thus, neither fit is unambiguously correct. Both include at least one parameter which is unexpected.

We have not yet completed a similar set of fits to $^{16}O(e,e'p_3)$, but we also expect dual solutions in this case as well.

We had previously discussed the possibility of measuring the cross sections for $^{12}C(\gamma,p)$ and $^{16}O(\gamma,p)$ using the tagged photon facility at the University of Illinois (UI). Given the tagged photon flux and our typical target thickness and telescope solid angles, the measurement should take ~100 hours. The UI group was receptive to the idea. However, due to other commitments on our part, particularly with respect to the recent Bates run, we have not yet made this measurement. Now it appears that measurements at UI are unlikely due to the fact that the UI accelerator will be permanently shut down by the end of 1990.

If it is impossible to make these measurements at UI before their shutdown, then we will make a formal proposal to the PAC at Saskatoon, which also has an operational tagged photon facility.

These measurements are straightforward, regardless of where they are to be made. All the necessary equipment is either in hand or is already being requested in conjunction with the Bates experiments discussed earlier. This experiment will constitute part of a Master's thesis project for one new student.

B.8 Future Experiments and Summary of Program

The experiments completed at Mainz, approved at Bates, and planned for the SHR are all part of a program of systematic studies of the charged particle decay of the GR's of the p-shell nuclei, ^{12}C and ^{16}O. The GR's of these two nuclei have been theoretically investigated by very many authors and are microscopically described as different linear combinations of the same 1p-1h states. For example, promotion of a particle from the 1p-shell to the 2s-1d orbits leads to the formation of GR's with J^π from 1^- up to 4^- in both nuclei. The 4^- resonances are the well known stretched configurations and have been studied with a number of other reactions, but their coincidence decay modes have not been observed.

Not only do we plan to study all of these resonances by varying q and ω, but also by varying the 1p-1h amplitudes through a comparison of these two nuclei. We have already discussed a first comparison of the $^{12}\mathrm{C}(e,e'p_0)$ and $^{16}\mathrm{O}(e,e'p_3)$ cross sections in section B.1. We plan to continue these comparisons to higher q and with polarized beam.

Thus, once the Bates SHR becomes fully operational, not only will we complete the ^{12}C work as proposed by us and endorsed by the PAC, but we will also propose to complete a similar set of measurements on ^{16}O. These measurements will achieve the last of our original goals and complete the program.

For these experiments we will request support for additional students. Several aspects of this work appear to be good projects for graduate theses. Since the basic equipment is in hand and working, future equipment requests will be limited to those necessary to maintain and upgrade the system as needed.

In summary, the giant resonance program is a vital continuing project. The continuation of the analysis of earlier Mainz data and the ongoing program at Bates, as outlined in the earlier sections, are expected to provide thesis projects for three new students starting during the next three years. Future experiments at Mainz will require additional students. All these students will also participate in the design and development of new detectors to be incorporated into the BLAST and CEBAF hardware.

Section C

DEEP INELASTIC SCATTERING STUDIES

Deep inelastic electron scattering has played an important role in the study of nuclear structure. Coincidence studies in the quasielastic region and above yield information on the wave functions of nucleons within the nucleus, both single particle orbitals and more complex many-body configurations. The quality of experimental results challenges models of nuclear structure, leading to an expansion of theoretical efforts and increased understanding of the observed phenomena.

Long range correlations are responsible for pairing of nucleons inside the nucleus. This long range coupling of nucleons introduces additional components to the nuclear wave function, leading to a depletion of occupancy below the fermi level, and a corresponding increase of occupancy in the higher lying orbitals. Our studies of knockout reactions to low lying bound states in the residual nucleus provide a direct measure of these occupations.

Short range correlations produce the high momentum components of the nuclear wave function. Reaction processes leading to ejection of several nucleons provide information about multinucleon structures at very short distances. Our $(e, e'p)$ results on ^{12}C provided the first semi-exclusive measurements to guide our understanding of these processes. Our new initiative in $(e, e'2p)$ will further constrain these processes by providing exclusive determination of the final state.

In order to quantify the interaction at short range we are embarking on an extensive program to study high momentum breakup reactions in several light systems. Electrodisintegration of the deuteron specifies the two nucleon isoscalar system. The trinucleon system provides channels for isoscalar and isovector currents, as well as three body degrees of freedom. Heavier systems provide the full complexity of the many body nuclear degrees of freedom. Control of beam and target polarization allows increased selectivity over the contributions to the hadronic current. Large acceptance detection provides a fully exclusive determination of the reaction.

The UNH Nuclear Physics group has become committed to a program of deep inelastic coincidence measurements. Our participation in the Bates studies of the quasielastic, dip, and Delta contributed to the success of those programs, now completed. Our initiative to study ^{16}O $(e, e'p)$ with high resolution at NIKHEF-K is nearing completion. Our analysis of that data at UNH is of an exceptionally high quality, and represents the first successful attempt at such an analysis at an external user facility. A few years ago we developed and proposed at several laboratories an ambitious program of triple coincidence studies of multinucleon reactions. As a result a pioneering experimental study of $(e, e'2p)$ reactions is now underway at NIKHEF. We are also pushing the development of multinucleon programs at Bates and CEBAF, with the intention of extending our initial measurements to continuous high energy beams, and nearly 4π acceptance. With the advent of the new facilities, this research will become the core of our program.

C.1 Quasielastic Proton Knockout from ^{16}O

The UNH Nuclear Physics group has recently completed a series of quasielastic $(e, e'p)$ measurements on the ^{16}O nucleus. The purpose of the experiment was to determine the extent of multiparticle-multihole contributions to the ^{16}O ground state wave function. These multiparticle configurations give rise to the population of the normally unoccupied s-d shell in ^{16}O. The quenching of the p-shell occupancy has also been studied in detail.

The data acquisition for this experiment was completed in the spring of 1988. The coincidence reaction was measured in parallel kinematics with a constant proton center of mass energy of 90 MeV. Keeping the energy of the ejected proton constant with respect to the residual ^{15}N nucleus eliminated relative uncertainties in the final state interaction between different kinematics. The proton spectral function was measured in the missing energy region $0 < E_m$ (MeV) < 40, and in the missing momentum region $-170 < P_m$ (MeV/c) < 270. One major innovation in the data acquisition was the use of liquid water (H_2O) as a target, thereby eliminating the unwanted contribution from "contaminant" nuclei in a compound target such as BeO or LiO. The target employed for the experiment (the waterfall target) was designed and built by collaborators at Mainz.[22,32] The singular H_2 coincidence response was easy to identify and subtract from the ^{16}O spectral function. At kinematics neighboring $P_m = 0$, where scattering from H_2 is known to dominate the spectral function, a target of heavy water (D_2O) was used. As a consequence, the recoiling neutron causes a substantial smearing of the hydrogen response, thereby allowing for the successful extraction of the oxygen spectra.

The reduction of the ^{16}O data was completed at UNH last spring (1989) using data analysis codes developed at NIKHEF. The ^{16}O analysis represented the first

successful migration of the NIKHEF codes to an external user facility. Much effort was devoted to removing the system-dependent features of these codes, as well as to their reorganization and optimization. What remains is a highly developed set of coincidence analysis codes, suitable for adaptation to the analysis of other coincidence data acquired on different spectrometers. These codes are available and could be readily transported to other US facilities with Unix computing environments. As part of our expanding role in the field of coincidence physics, we at UNH plan to continue our commitment to the development and distribution of improved software.

An example of a missing energy spectrum is shown in Fig. C.1, where several discrete states are observed. Momentum distributions have been extracted for 11 discrete states in all. The two strongest states, at excitation energy $E_x = 0.0$ MeV and $E_x = 6.3$ MeV, represent proton knockout from the $1p_{1/2}$ and $1p_{3/2}$ orbitals in ^{16}O respectively. Proton knockout from the $1s_{1/2}$ orbital occurs at much higher separation energies, most of which was outside of the spectrometer acceptance of our experiment. An independent study of the $^{16}O(e,e'p)$ reaction at Saclay[25] shows a broad 1s peak extending from a missing energy of 30 MeV all the way to 70 MeV.

Of particular interest is the positive parity doublet at an excitation energy of 5.29 MeV. Two states are known to exist in this region, but the difference in excitation energies, 30 KeV, is much less than the experimental energy resolution of about 150 KeV. The momentum distribution for these states is shown in Fig. C.2. Since the $1/2^+$ state arises from an $\ell = 0$ transfer, and the $5/2^+$ arises from an $\ell = 2$ transfer, their momentum space wave functions are easily distinguished.

The analysis of the ^{16}O spectral function within the framework of the Distorted Wave Impulse Approximation (DWIA) requires specification of the optical potential, the nuclear structure, and assumes an impulse reaction mechanism. Normally the optical potential is given by a Woods-Saxon well with strengths and radii optimized to fit elastic proton scattering data. Nuclear structure of the overlap between the A and A-1 is usually specified as a single particle orbital in an adjustable Woods-Saxon well. Spectroscopic strengths and rms radii of the bound state wave functions resulting from this analysis are listed in Table C.1 for each of the observed discrete states. We are in the process of testing the validity of each assumption that comprises the analysis.

In Fig. C.3, the momentum distributions for the two p-shell states are shown together with a DWIA calculation using two different optical models.[26,29] Both momentum distributions are described exceptionally well by the DWIA calculation, both at positive and negative missing momenta. The spectroscopic strengths extracted from these two states are 1.27 and 2.25 for the $1p_{1/2}$ and $1p_{3/2}$ states respectively, with fitted uncertainties less than one percent of their value. It is interesting to note that the more deeply bound $1p_{3/2}$ orbital is more heavily depleted (44%), relative to the IPSM sum

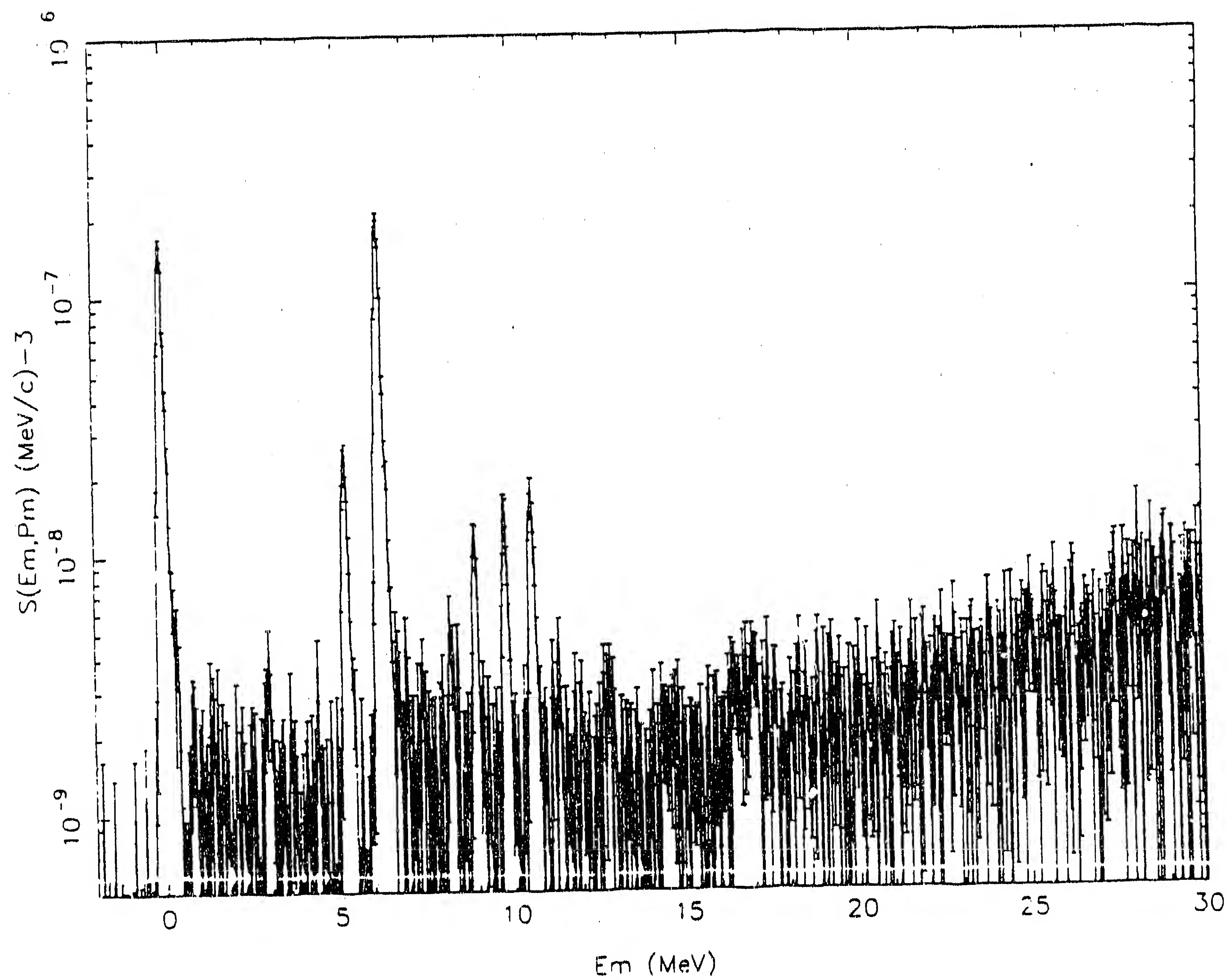

Fig. C.1 Missing energy spectrum of the $^{16}O(e,e'p)$ reaction at the kinematics centered about P_m = 120 MeV/c.

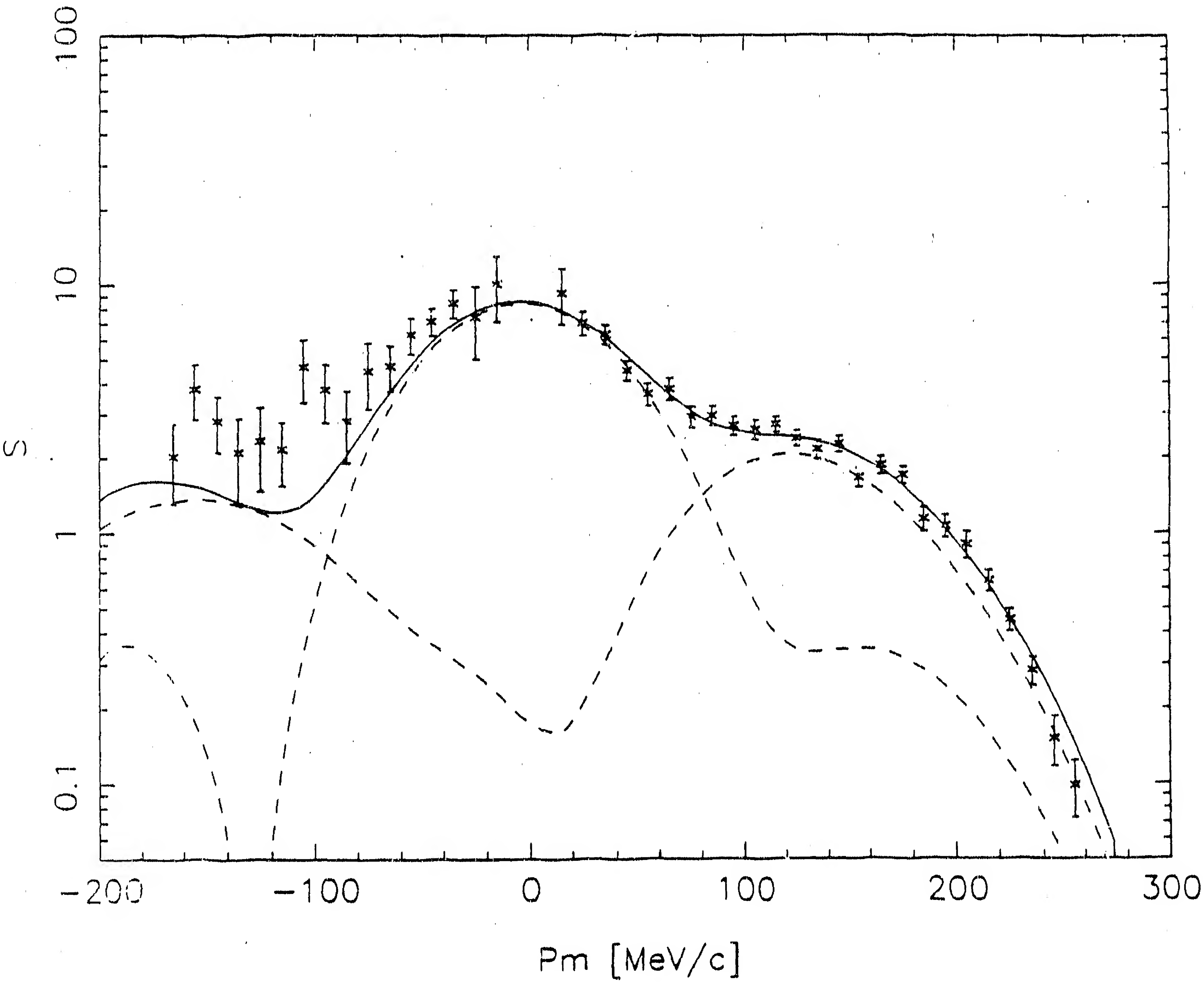

Fig. C.2 The momentum distribution for the positive parity doublet at $E_x = 5.3$ MeV. The solid curve is the incoherent sum of the two dotted curves which represent DWIA calculations of the $2s_{1/2}$ and $1d_{5/2}$ momentum distribution with the Schwandt optical potential.[29]

E_x MeV	spin/parity	Spectroscopic Strength	radius fm
0.00	$1/2^-$	1.274(13)	2.688(37)
5.27	$5/2^+$	0.112(2)	3.429(50)
5.29	$1/2^+$	0.038(1)	3.502(55)
6.32	$3/2^-$	2.250(18)	2.695(18)
8.31	$1/2^+$	0.024(2)	1.82(24)
9.05	$1/2^+$	0.037(3)	1.80(24)
9.93	$3/2^-$	0.130(3)	2.741(56)
10.70	$3/2^-$	0.207(2)	2.597(39)
12.10	$5/2^+$	0.021(2)	3.24(18)
12.55	$5/2^+$	0.023(7)	2.96(11)
12.92	$3/2^-$	0.034(3)	2.62(19)

Table C.1 Discrete states observed in the reaction $^{16}O(e,e'p)$.

rule limit, than the $1p_{1/2}$ orbital (36%). This effect is most likely due to complicated multiparticle-multihole configurations in the ^{16}O wave function, which we plan to investigate thoroughly with shell model calculations developed here at UNH (discussed in section D).

We recently tested an optical potential derived by Kelly that is constrained not only by proton elastic scattering, but inelastic scattering as well. The form of the optical potential is explicitly not Woods-Saxon, but rather a shape derived from microscopic folding of the Paris potential over the nuclear density, including effects of Pauli blocking. Preliminary calculations indicate the spectroscopic strengths derived from the data analysis are significantly enhanced, to the levels expected from microscopic theory. We have become convinced that a full incorporation of this development into the standard $(e,e'p)$ analysis framework may finally achieve the promise of the $(e,e'p)$ reaction as an absolutely quantitative tool.

Several quasielastic $(e,e'p)$ studies conducted at NIKHEF and Saclay,[24,30] observed excess strength in the negative missing momentum spectral function, interpreted as an enhancement in the transverse response function. We observed no such enhancement in our analysis. This arouses the suspicion that the explanation of this effect may lie in the description of the final state interaction. Indeed, it was found in the UNH analysis that slight modifications in the optical potential created substantial effects in the calculated momentum distributions. With our study of optical potentials including reanalysis of

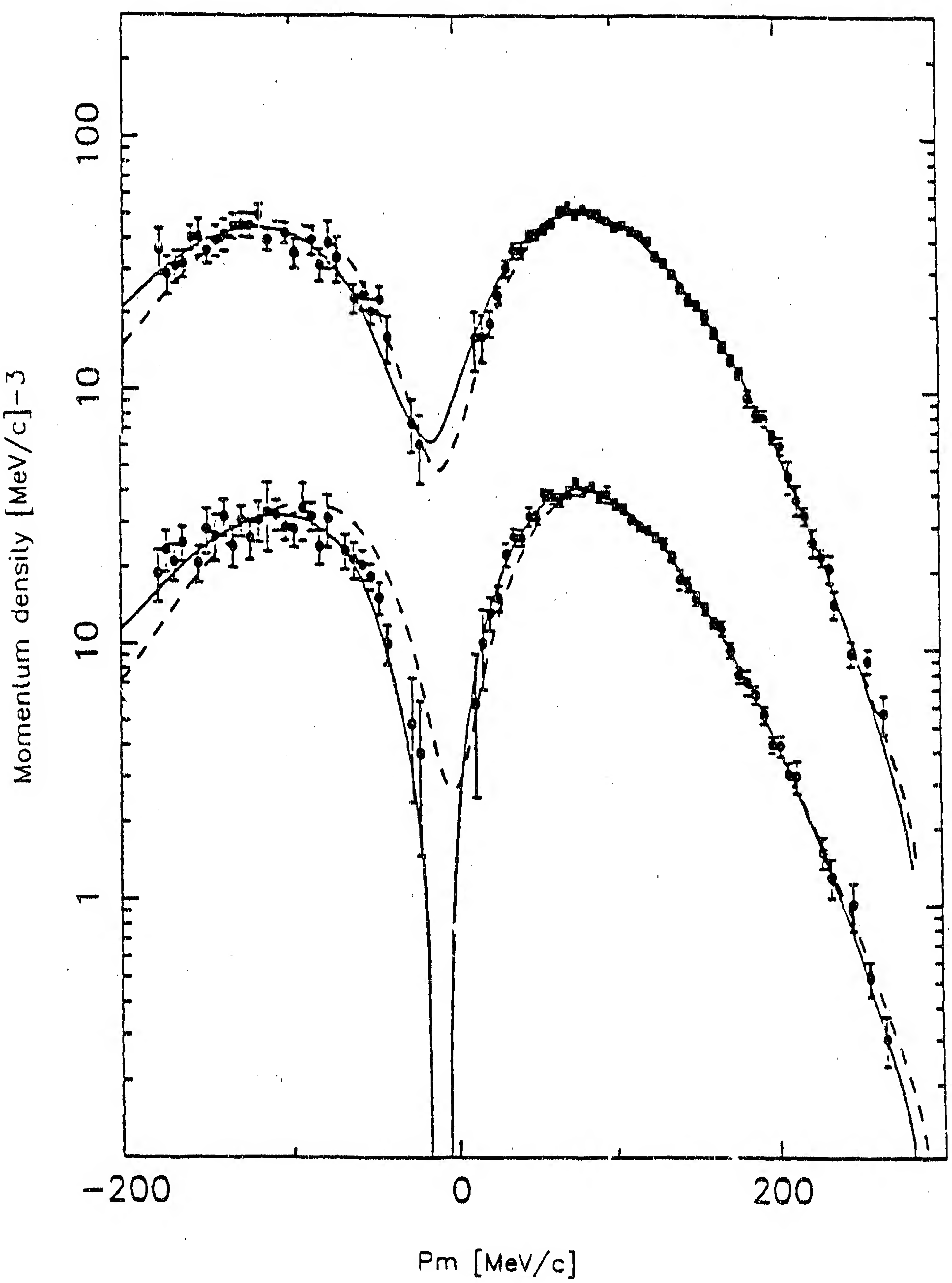

Fig. C.3 The momentum distributions for the 1p states in ^{15}N. The curves represent DWIA calculations using the optical model parameterizations of Schwandt[29] and Jackson[26]

(p,p') data now underway at UNH, we hope to determine whether or not information regarding anomalous response function enhancements can be extracted with confidence from $(e,e'p)$ data.

In order to extract reliable spectroscopic information from the weak states in ^{16}O, the contribution to the observed final state due to two-step processes must be estimated. It is possible, for instance, that a proton can be knocked out of the highly populated p-shell, and then in turn inelastically excite the residual ^{15}N nucleus. From the measured asymptotic kinematics, the proton then appears to have been knocked out of an orbit with a different binding energy. Results from other $(e,e'p)$ studies have shown[23] that while the effects are small for the highly populated orbitals below the fermi level, they can be quite substantial for the weak states. The effect of channel couplings in weak state transitions has been found[30] to be as high as 30 percent in a similar $(e,e'p)$ study on ^{12}C. Nevertheless in the case of ^{16}O, a complete lack of observed $7/2^+$ strength in the ^{15}N spectrum gives some measure of the lack of two-step processes. One would expect, on the basis of the weak coupling model, that if the $5/2^+$ is populated indirectly via the $(e,e'p)(p,p')$ two-step reaction, then its weak coupling partner, the $7/2^+$, would also appear in the spectrum. This is not the case. Regions in the ^{15}N spectrum in which $7/2^+$ strength has been observed with other reactions show no structure in the $(e,e'p)$ reaction.

A sample coupled-channels impulse approximation (CCIA) calculation for the positive parity doublet at $E_x = 5.3$ MeV in ^{16}O is shown in Fig. C.4. The effect is quite large for the $1d_{5/2}$ state, and could lead to a 50 percent reduction of the spectroscopic strength relative to the pure DWIA calculation. Since the CCIA calculations depend heavily on the coupling strengths between the states in ^{15}N, it is of the utmost importance that these strengths be determined accurately. Unfortunately, very little information exists in the literature concerning scattering experiments from ^{15}N. To alleviate this problem, our collaborators at NIKHEF are currently reanalyzing old $^{15}N(e,e')$ data taken at NIKHEF[33] so that these strengths may be determined directly. A consistent description of all weak states, including the unobserved $7/2^+$ state, must be obtained before confidence can be placed in the calculation.

Work has been completed to adapt the Operator Renormalization Approximation for Shell Models (ORASM), discussed in section D, to the problem of nucleon knockout reactions. We are currently in the process of migrating this nuclear structure package to the group's new DEC workstations. It is anticipated that calculations will be started this summer to try to provide an improved theoretical description of the ^{16}O experimental results, in particular the overlap between complete ^{16}O and ^{15}N wavefunctions.

The oxygen analysis continues to provide a wealth of interesting information pertaining to nuclear structure and to the $(e,e'p)$ reaction. The analysis is near comple-

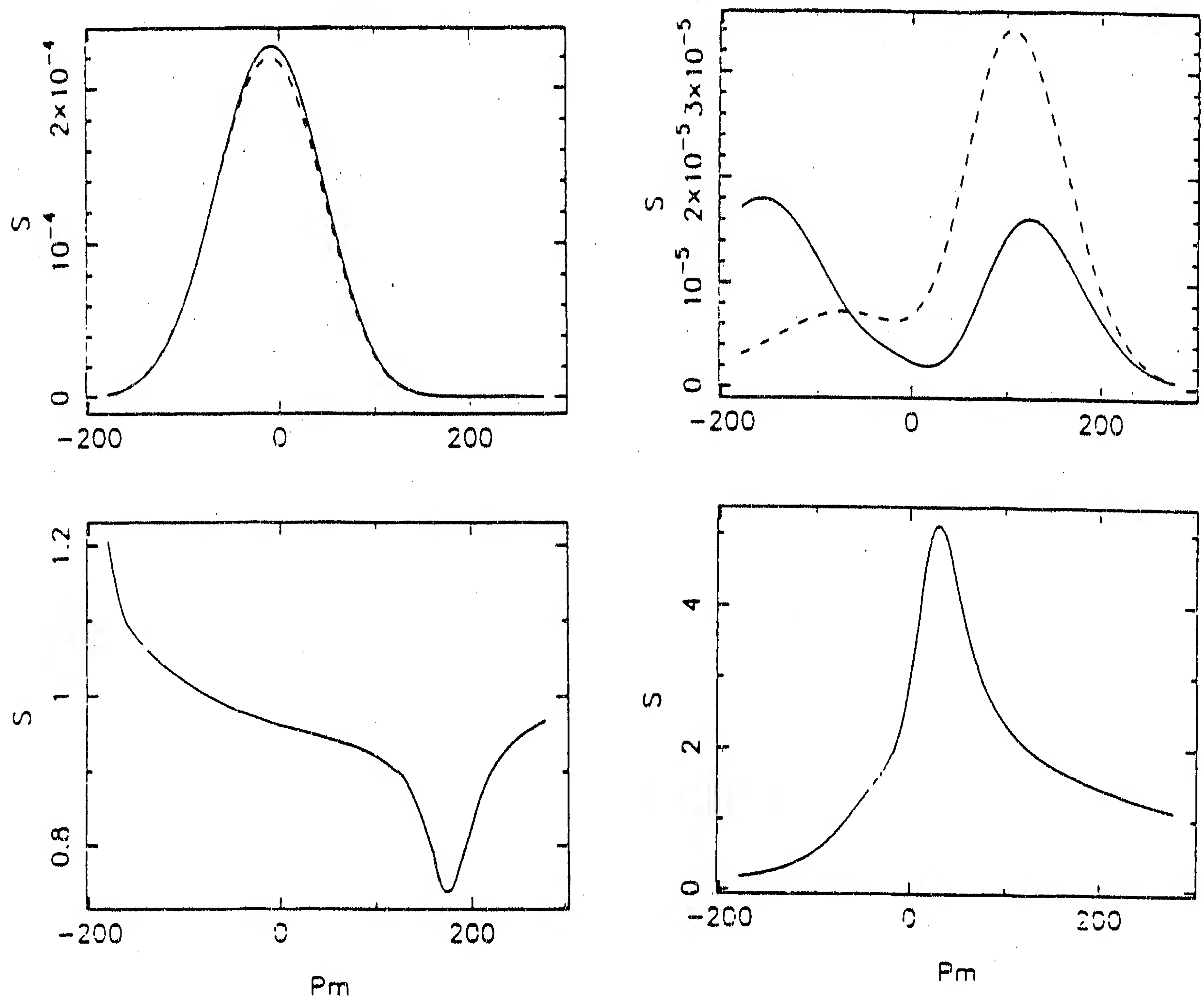

Fig. C.4 Coupled channels calculation for the ^{15}N positive parity doublet at E_x=5.3 MeV. The solid curve represents DWIA curve only. The dotted line is the same calculation with the effects of the channel couplings included (DWIA+CCIA). Beneath, the ratio (DWIA+CCIA)/DWIA is plotted to show the regions where the coupled channels calculations produce the greatest effects.

tion, awaiting only the final coupled channels calculations and the results of the optical potential investigation discussed above. The first publication on the ^{16}O project is expected to be completed before the end of the summer (1990). This work is the thesis project of one UNH graduate student, Mark Leuschner, who anticipates finishing his work by the end of this year (December 1990).

C.2 Proton Knockout from ^{12}C

The UNH group has collaborated on a program of $^{12}C(e, e'p)$ reaction studies at Bates. Initially UNH participated through the development of coincidence capability with MEPS and OHIPS. John Calarco designed the original coincidence electronics hardware, and Bill Hersman contributed to the acquisition code. Our interest and participation have continued throughout the program. During the past few years the MIT studies have concentrated mainly on the Delta region and the quasielastic region at very high momentum transfers. Both studies are now complete, and were the thesis projects of two MIT students, Hossain Baghaei and Larry Weinstein.

These experiments provide a complementary picture of nucleon currents in the nucleus. Whereas the NIKHEF facility is renowned for its exceptional energy resolution, the Bates facility has a higher beam energy and a larger acceptance. As a result, NIKHEF experiments are generally performed in order to extract spectroscopic information from discrete states, whereas the MIT experiments were conducted with the intent of outlining the broader features of the $(e, e'p)$ reaction throughout a much larger kinematical domain. NIKHEF excels at probing one-body properties, while Bates has focussed on many body currents.

Two measurements of the $^{12}C(e, e'p)$ reaction were made in the Delta region.[21] The first measurement was at the high side of the dip region, while the second was on the Delta peak. Missing energy spectra for these two kinematics are shown in Fig. C.5. In contrast to the results from the quasielastic and dip regions, there appears to be no signature of the single nucleon reaction mechanism in these spectra. The sharp 1p peak is not present as it was in the lower energy transfer kinematics. The spectra both show the onset of Delta excitation, however, via the strong peak beyond the pion production threshold. The strength in the region below this threshold, then, is apparently the result of multinucleon reaction processes.

From the earlier work of Paul Ulmer[31] in the quasielastic region, it was observed that the longitudinal response function vanished beyond a missing energy of about 50 MeV, while the transverse response function had a considerable strength out the measured limit of 65 MeV. From this observation it was concluded that the single-particle reaction mechanism ended at 50 MeV, and that the coincidence strength beyond that

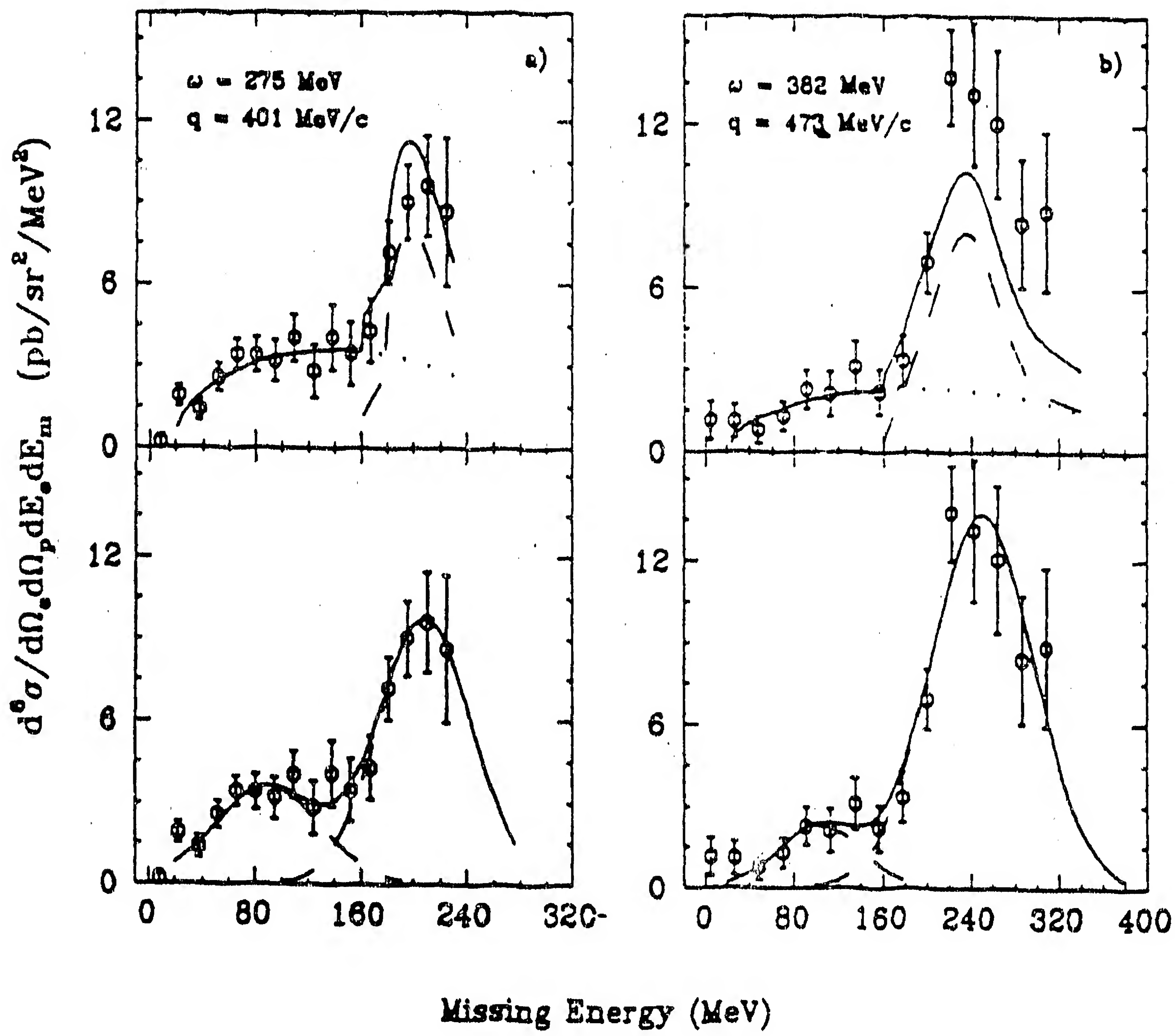

Fig. C.5 Missing energy spectra for the $^{12}C(e,e'p)$ reaction in the Delta region. The curves are fits of the data to a quasifree Delta production calculation.

point arose from multiparticle reaction mechanisms. This observation, in part, provided the motivation for an extended study of the kinematical nature of the multiparticle reaction mechanism.

The quasielastic $^{12}C(e,e'p)$ reaction was measured in parallel kinematics at five momentum transfers ranging from 585 to 1000 MeV/c. At these high momentum transfers the inclusive response is featureless, since the quasielastic, dip, and delta have comparable strength. Missing energy spectra for four different kinematics are shown in Fig. C.6. It is interesting to note that there is no apparent onset of strength at the pion threshold (about 150 MeV) in any of the kinematics, as was the case in the Delta region. It appears, then, that Delta production doesn't play a role in the reaction at these kinematics. Instead, we must conclude that the strength beyond the 1s peak is entirely the result of multinucleon processes. Furthermore, the ratio of the single particle strength (below 50 MeV) to the continuum strength decreases with increasing momentum and energy transfer. Apparently, multinucleon processes become increasingly important at these kinematics.

The MIT studies underscore the need for an intense systematic study of the kinematical regions extending from the quasielastic region and beyond. It is our hope that the new generation of medium energy electron accelerators and detectors will provide us with the opportunity to do so.

C.3 The Triple-Coincidence $(e,e'2p)$ Reaction

Single coincidence $(e,e'p)$ studies in the quasielastic region and above have provided new information pertaining to multinucleon currents in nuclei. These experiments have shown that processes beyond the single nucleon knockout channel contribute significantly to the cross section.[28,31] It is now believed that even two-nucleon emission is insufficient to explain the strength, providing evidence for three body currents. To investigate the complexities of these multiparticle reaction channels it is necessary to measure the final reaction state more exclusively. It is our hope that an investigation of $(e,e'2p)$ reactions will elucidate the role of short range correlations and multiparticle configurations in nuclear structure.

At the end of 1987, the UNH group proposed at Bates and NIKHEF the first triple coincidence measurements of $(e,e'2p)$. Both PACs strongly endorsed the physics goals. Due to the highly developed instrumentation program at NIKHEF, the project was accepted at that laboratory. (The project was deferred at Bates due to the lack of instrumentation resources, and concerns about high uncharacterized backgrounds in the experimental halls.) Our proposal motivates an exclusive study of two nucleon knockout, as a measure of nucleon-nucleon correlations in the deep inelastic region

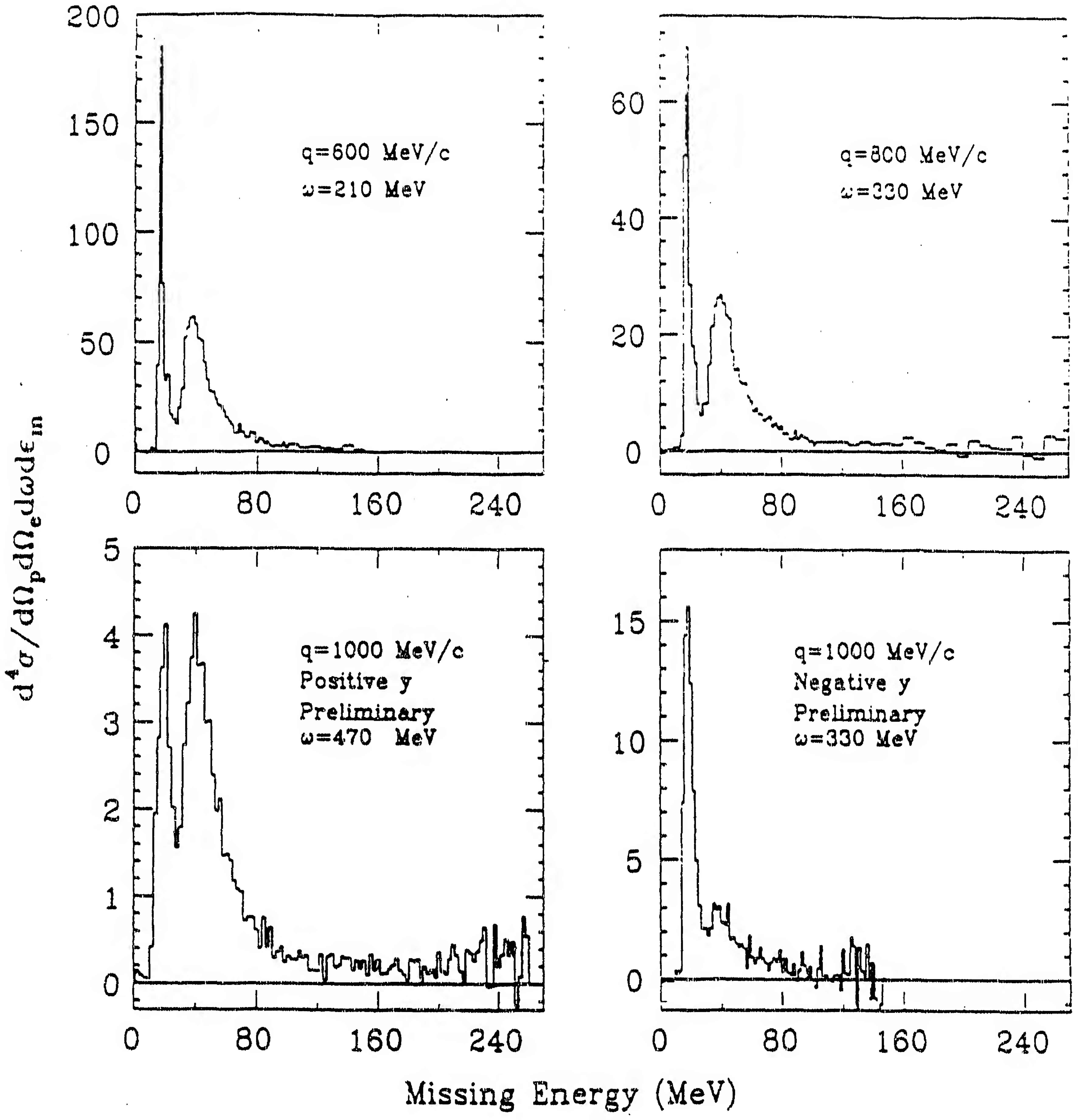

Fig. C.6 Missing energy spectra of the quasielastic $^{12}C(e, e'p)$ reaction at large momentum transfers. The sharp peak at low missing energy corresponds to 1p knockout, while the broad peak at higher missing energies corresponds to 1s knockout.[34]

of ^{12}C. We have formed a collaboration with the group at NIKHEF and the Free University, and proposed to make a similar measurement to explore delta damping mechanisms in ^{12}C. We expect that these two studies will shed some light on the nature of the reaction mechanisms responsible for the strength anomalies observed in $(e, e'p)$ studies.

The first production run of the $(e, e'2p)$ program at NIKHEF-K was completed in June of 1989. The two ejected protons were detected in a set of highly segmented, large acceptance (40 msr) plastic scintillation counters (Fig. C.7) which were developed at NIKHEF. Each detector consists of several layers of scintillators which determine the angle and energy of the protons. The angular resolution of the proton detectors is on the order of 1/2 degree, while the energy resolution was recently shown to be 2 MeV. This energy resolution will allow the exclusive identification of final states.

The kinematics selected for the triple coincidence experiment favored the detection of protons which are initially correlated back-to-back in the target rest frame. The backward angle hadron detector was also positioned at angles backward and forward of this position, in order that an angular distribution could be obtained with respect to the back-to-back proton orientation.

In addition to the triple coincidence reaction, the three possible combinations of twofold coincidences were also recorded simultaneously. The $(e, e'p)$ information thus obtained is also of interest. One combination, if viewed with respect to exclusive $(e, e'p)$ kinematics, corresponded to the detection of protons with an initial (bound) momentum of more than 600 MeV/c. This momentum is more than twice the fermi momentum of light nuclei such as ^{12}C. A preliminary missing energy spectrum for this kinematics is shown in Fig. C.8. The peaks for proton removal from the 1s and 1p shell are clearly distinguishable.

The data are currently in a preliminary stage of analysis at NIKHEF. With over 100 independent detection channels, the timing and energy calibration processes are understandably formidable. A new database management system, just recently written and installed by UNH, has revolutionized this procedure. Progress on the detector calibration is now expected to accelerate considerably.

At present, track identification and path reconstruction routines are at a high level of development at NIKHEF, but still not fully functional. The major problem in the path reconstruction has been how to reconstruct the proton momentum in events where one of the scintillator layers in the detector fails to record the passage of the proton. A procedure for reconstructing the proton momentum has been developed and the problem should be solved shortly. It is anticipated that the full data analysis system will be completed, and operational, in time to yield results before the next acquisition

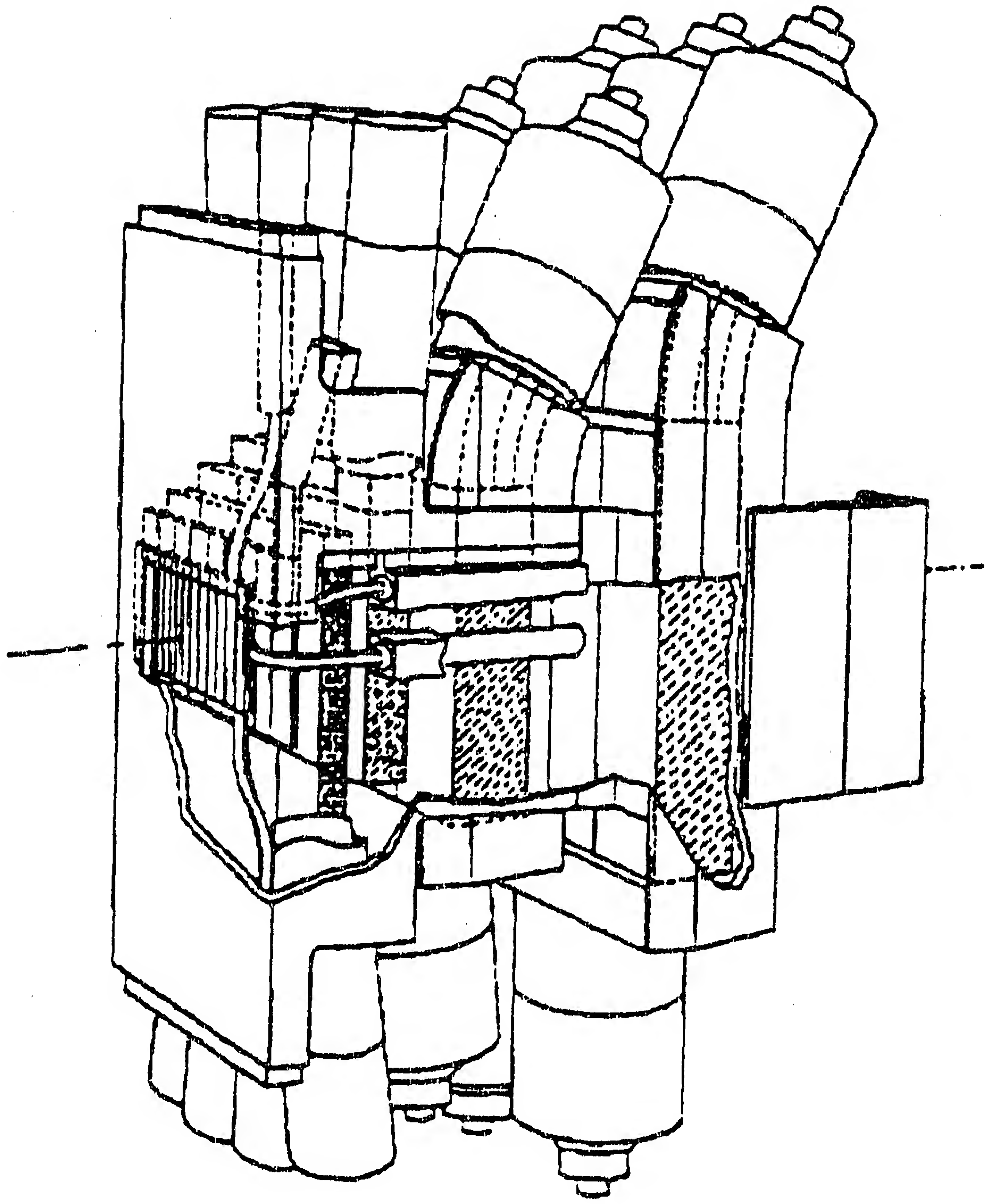

Fig. C.7 The hadron detector used for the NIKHEF $(e, e'2p)$ experiment. The scintillator layers are shown along with their light tubes and photo-multipliers.

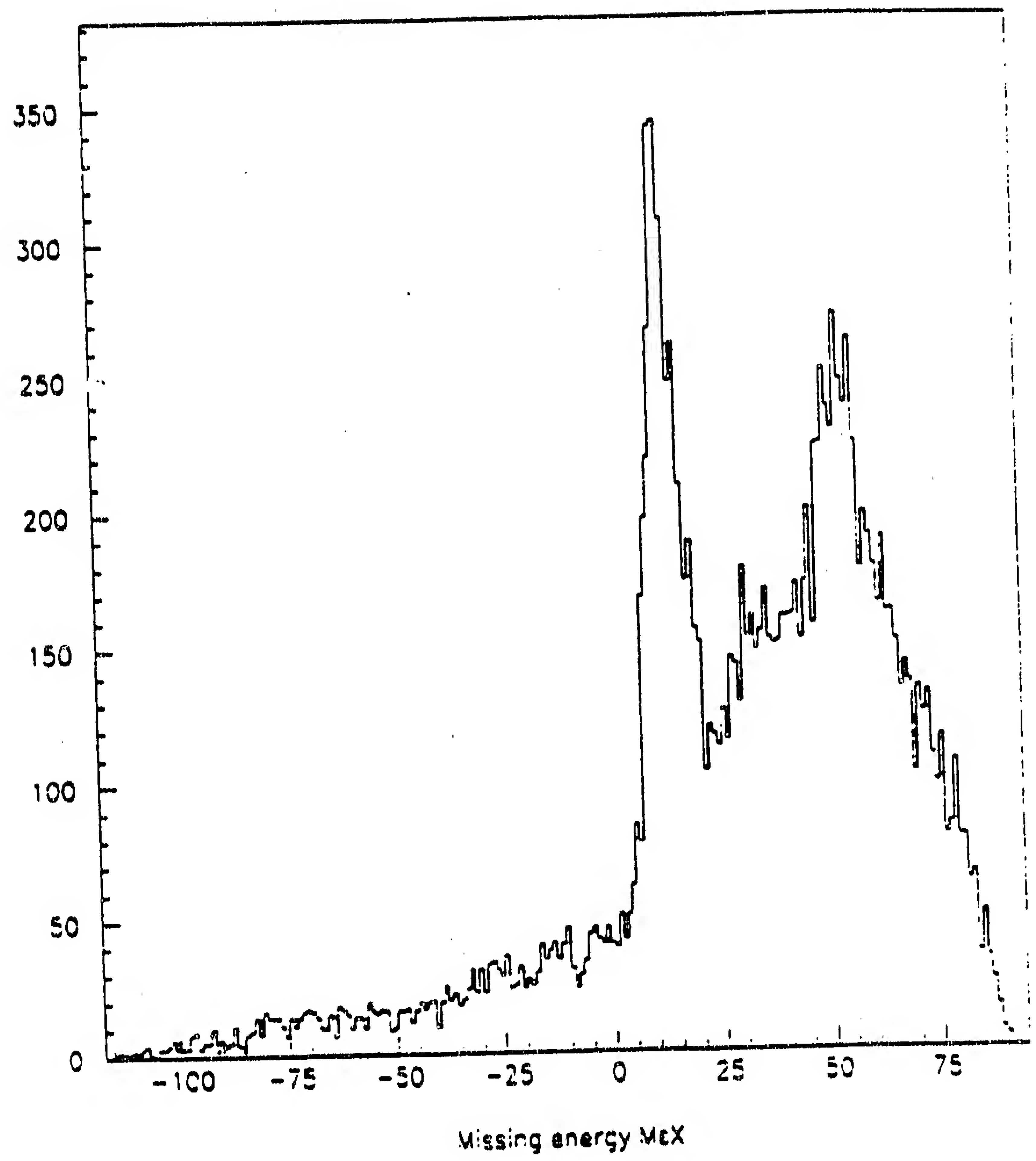

Fig. C.8 A preliminary missing energy spectrum for the high missing momentum ($P_m > 600$ MeV/c) kinematics. The sharp peak is due to proton knockout from the 1p shell, while the broad peak at higher missing energies is due to proton knockout from the 1s shell in ^{12}C.

run.

Current indications are that approximately one true triple coincidence event per hour was recorded during the first experiment, adding up to a total of about 150 triple coincident events. This is sufficient to characterize the scale of the reaction process, and begin to understand its kinematic distribution. This is important for guiding the development of instrumentation for the new continuous beam laboratories. The data analysis will most likely concentrate on the wealth of $(e, e'p)$ information recorded during the experiment. In addition, we hope to obtain an improved understanding of the detection facilities. Approximately 3/4 of the allotted beamtime during the first run was used in debugging the detector electronics and experiment control software. The prospects for a more successful second run, to be conducted this coming fall, are much greater due to improved on-line monitoring and control, and improved on-line data analysis.

UNH's involvement in the NIKHEF collaboration has been concentrated mainly in two regions. During his sabbatical in Mainz, John Calarco traveled to NIKHEF several times to work on a new tube-base design to reduce photo-multiplier baseline shift and gain shift instabilities. His design was implemented during the first run last year, and from the appearance of the raw data, appears to have worked well. Energy resolution in the proton detectors, which was observed to be somewhat poor during prior test runs without the new tube-bases, had improved considerably during the actual experiment.

Second, the UNH group has also invested considerable time in developing software for the triple coincidence project. As mentioned above, a new database management system has recently been interfaced with all of the data analysis codes, and is now providing a dramatic improvement in organization and convenience.

For more than a year UNH has also been working on Monte Carlo calculations to simulate $(e, e'2p)$ physics. We now have a completed family of codes which support a wide range of physics applications, including count rate and background estimation, kinematic optimization, detector simulation and phase space calculation, and predictions of on-line spectra. Applications have also be developed to motivate and support our proposed programs at CEBAF and Bates. Several calculations have been completed using Laget's description of the $(e, e'2p)$ reaction.[27] We feel that reliable simulations are a key ingredient in a successful nuclear physics experimental project, and we plan to continue a substantial effort in the development of these capabilities.

UNH has been committed during these past three years to the $(e, e'2p)$ collaboration at NIKHEF. Our run, currently scheduled for this September, may complete the measurement. The data analysis, much of it applicable to the programs at the next generation accelerators, will require an extensive effort during the next three years. It

is expected that a new post-doc, to be hired late this summer, will become involved in the acquisition for the upcoming run. This post-doc should then lead the analysis of the data, which by agreement with our collaborators will be the primary responsibility of the UNH group. We also hope to attract at least one new graduate student to the project, replacing Mark Leuschner who is graduating.

We feel that a major benefit of these experiments at NIKHEF has been to provide the UNH group with experience in the field of high multiplicity data acquisition and data analysis. These experiments are important stepping stones to our proposed future programs at CEBAF and Bates, particularly in contributing to their large acceptance detectors. The UNH group stands in a unique position within the American nuclear physics community as a result of our leading the NIKHEF triple coincidence program.

C.4 Deuteron Electrodisintegration

The primary goal of nuclear physics is a comprehensive description of nuclei. The basis of this description rests, first, on a fundamental characterization of the hadronic constituents. Secondly, the strong interaction acting between the constituents determines the structure of the composite nucleus. It also mediates the dynamical modifications to those structures and to the constituents themselves. Experimental investigations must select a system, and a probe of that system, which has the selectivity to isolate properties of the constituents, interactions, and composite structures, and characterize their degrees of freedom.

The deuteron is the lightest bound nuclear system. The principal elements of nuclear physics studies are contained in the structure of the deuteron, without the complicating effects of three body forces and many nucleon structure. The neutron in deuterium can be accessed to determine its properties. Similarly, the properties of the proton in the bound system can be measured and compared with the free proton, to test for modifications. The role played by meson, delta, and isobar degrees of freedom can be examined by comparing coherent responses to calculations with and without these terms, or by coupling directly to the particles and producing a signature in the final state.

We have joined a collaboration, led at MIT, to make a high precision comprehensive and coherent measurement of the individual response functions (R_L, R_T, R_{LT}, R_{TT}, R'_{LT}) for the $d(e,e'p)$ reaction. The reaction will be measured over a wide range of electron kinematics (both quasielastic and non-QE), proton initial momenta, and proton-virtual photon angles in order to properly guide and constrain theoretical calculations. The separated response functions will give us much more complete information about the different aspects of the n–p system including meson exchange currents (MEC), isobar configurations (IC), and the nucleon-nucleon (NN) potential.

In Fabian and Arenhövel's[35] study of the electrodisintegration of the deuteron, they showed that the different response functions are sensitive to final state interactions, and to the effects from MEC and IC. Generally they show that R_L and R_{LT} are sensitive to the final state interactions; *i.e.* the largest differences occur between the PWBA and the calculations where the final state interaction is described using a realistic NN potential such as the Paris or the Reid Soft Core potentials. The transverse response functions seem mostly sensitive to MEC and IC. However one must distinguish between two general kinematic regions. The first is given by $\mathrm{E}_{\mathrm{np}}^{\mathrm{cm}} = q_{\mathrm{cm}}^2/4000$. This is the region where ω falls on the quasielastic ridge in (e, e'). The second region is at considerably higher values of ω. In our proposal $\mathrm{E}_{\mathrm{np}}^{\mathrm{cm}} = 6 \cdot q_{\mathrm{cm}}^2/4000$ for this second region.

In the region of the quasielastic ridge, the response functions are most sensitive to the conventional currents of nucleon motion, the nucleonic structure of the deuteron, and the final state interactions. The sensitivity to MEC and IC is greatly reduced. In contrast, many of the response functions at the high ω region show strong sensitivity to MEC and IC. The inclusion of MEC and IC in the calculation for R_T changes the response over an order of magnitude. R_{TT} shows little sensitivity to FSI, but the sensitivity to MEC and IC is very large, enabling a measurement of even modest precision to be important. R'_{LT} is always sensitive to FSI and vanishes in PWBA. However, at high ω we also have a very strong dependence on the MEC and IC components of the current.

The measurements will be performed in the North Hall using ELSSY as the electron spectrometer, and the four out-of-plane spectrometers OOPS. A newly developed cryogenic liquid-deuterium target will be used, mounted in the tritium target system. The 50 W refrigerator will allow the target to accommodate 20 μA of beam current.

The experiment was approved at the January 1990 PAC meeting. "PAC strongly supports a systematic program of precise measurements of $(e, e'p)$ structure functions in deuterium. This proposal represents a major extension to out-of-plane response, and non-quasi-free kinematics. The beam time request is large, so that this is to be viewed as a proposal for a long-term coherent program."

During the early stages of OOPS development, UNH participated in the OOPS meetings, and served on a Technical Advisory Panel evaluating the OOPS project. Recently, however, the UNH group, due to its strong involvement in BLAST development at Bates has not had the resources to participate in the OOPS construction. Nevertheless we do intend to participate in these studies of deuterium as fully as possible. We are also developing a proposal (discussed below) to extend these measurements to extract polarization response functions using polarized deuterium internal gas targets in the Bates South Hall Ring using the BLAST detector.

C.5 Direct Reactions Using Silicon Surface Barrier Detectors

The UNH giant resonance program has developed the use of silicon surface barrier detectors for measuring energies and angular distributions of decay protons. This detection technique also has the potential for use in direct reactions. If the detected particle is a large cluster, the stopping power, resolution, and acceptance in energy and solid angle of silicon detectors make them the detectors of choice. This occurs in the direct knockout of alpha clusters, and knockout reactions whose kinematics are determined by the recoiling residual nucleus. We have proposed two experiments of these types at Bates.

C.5.1 *Direct Knockout of Clusters via* $(e, e'\alpha)$

The clustering of nucleons into α-particles has been known to be an important aspect of the structure of light nuclei for some time (see, *e.g.*, Bromley[36] and the references therein). The symmetries inherent in the nucleonic shell model wave-functions result in a strong overlap with four-nucleon correlations coupled to J=0,T=0. Recent $(p, p'\alpha)$ experiments[37] indicate that the probabilities of finding α's in light nuclei (spectroscopic factors) are enhanced beyond those predicted in shell model calculations,[38,39,40,41] possibly because the lower average nuclear densities in this region of nuclei (due to the large surface to volume ratio) encourage clustering, and a coalescence into a tightly bound spinless system of four nucleons is the most likely manifestation of this process.

More recently, the Interacting Boson Approximation (IBA) description of the structure of heavier nuclei has suggested (see, *e.g.*, Dussel, *et al.*[42]) that there is significant clustering of nucleons into α's in the surface region of these nuclei. Again, this process is most likely in a region of reduced density. There is some evidence that this is indeed the case from measurements of inclusive (p, α) production from Sm isotopes.[43]

We propose to make measurements of the $(e, e'\alpha)$ cross sections in selected nuclei using the Bates high energy ($\sim$ 900 MeV) electron beam. The use of the higher energy will allow:

1. the scattering to be carried out at as forward an angle as possible, thereby maintaining a reasonable primary scattering cross section while
2. the momentum transfer is increased to reduce α final state interactions (FSI).

The purpose of these measurements is multifold. First, they will yield, at the very least, the relative probabilities (spectroscopic factors) for finding α's for a range of light nuclei. Second, they will yield the distributions of these probabilities as a function of the initial α momentum, p_i, in the target nucleus. The systematic variation of these

distributions will provide information on the effective potentials binding these clusters. Third, the spatial distribution of the struck α could be studied by varying the momentum transfer, q, while keeping p_i fixed (although we do not propose measurements over a wide range of q). Finally, in heavy nuclei, observation of α knockout from the surface will provide a direct test of a prediction of the IBA.

To date, only the first two points mentioned above have been studied, and there are sufficient discrepancies and open questions to warrant additional work. The second two points have not been directly attacked at all. All previously published exclusive α knockout measurements have been from light to medium weight nuclei, and almost all as the result of hadron scattering, *e.g.*, the $(p,p'\alpha)$,[37] or using $(e,e'\alpha)$ reactions with lower energy ($\sim$ 500 MeV) electron beams[44] than available at Bates. The hadron induced reactions suffer from the strong interaction of both the incident and scattered proton, as well as the knocked-out α, which leads to more uncertainties in the interpretation of the results. The only previous published $(e,e'\alpha)$ measurements[44] produced outgoing α kinetic energies so low that resonance effects would be expected to be strong. By increasing q, the knocked-out α is still strongly absorbed in escaping from the nucleus, but the absorption is at least expected to be a smooth function of energy, as in the case of the proton induced knock-out, rather than show resonance effects. However increasing q at fixed bombarding energy leads to a strong reduction in the count rates.

Furthermore, while the previous measurements clearly show, at least qualitatively, that α clustering is strong in light nuclei, particularly in the $p-$shell, there are questions and discrepancies remaining. The $(p,p'\alpha)$ results[37] indicate large spectroscopic factors which exceed theoretical ones by up to a factor of $\sim$ 10. These measurements cover selected nuclei from ^{12}C to ^{66}Zn. The Saclay $(e,e'\alpha)$ measurements[44] on ^{6}Li were followed by some preliminary work (also at Saclay, but unpublished[45]) at higher q (=2.15 fm^{-1}) on ^{6}Li and at the lower q on ^{9}Be. These results seem to indicate that the spectroscopic factors are:

1. roughly the same for both nuclei,
2. significantly smaller than subsequently observed in the higher masses by the $(p,p'\alpha)$ studies;[37] and
3. strongly dependent on kinematics, probably indicating the importance of a final state interaction.

The $(e,e'\alpha)$ measurements[44,45] found the Fermi momentum, k_F, to be $\approx$ 35 and 55 MeV/c in ^{6}Li and ^{9}Be, respectively. The $(p,p'\alpha)$ results indicate a rather constant $k_F \approx 50$ MeV/c for the range of targets studied. It is possible that multistep processes are contributing in the $(p,p'\alpha)$ reactions. In fact, it has been shown from a comparison of $(p,p'p)$ and $(e,e'p)$ experiments[46] on ^{12}C, that final states are excited in the hadron

induced reaction that are absent in the electromagnetic process, indicating that multistep processes do indeed contribute in the former. Thus, electrons provide a cleaner probe for initiating knockout reactions.

There are no previous measurements of $(e, e'\alpha)$ from any nuclei heavier than Zn. Thus, this mass region is virgin territory.

The first measurements proposed for a feasibility study and approved for 100 hours by the Bates PAC will be made on nuclei overlapping those studied via $(p, p'\alpha)$ and at a similar outgoing T_α. Thus, we expect the FSI for the outgoing α to be the same in the two studies. In this way a direct comparison can be made between results obtained for the two different probes. This will provide a test of the method. In subsequent work, we will then extend these studies into the rare earth region.

We have the necessary hardware for the first phase of the experiment, which is basically to prove feasibility. The necessary detectors and electronics are a small subset of that used for the giant resonance studies. If it is successful, we plan to purchase and use some silicon strip detectors in conjunction with our SSB detectors to give a simultaneous measurement of energy and position within the acceptance of the detector. This second phase will be a major part of a thesis project for one new student.

C.5.2 *Threshold Pion Production*

We have proposed to the Bates PAC that we will make measurements of charged pion production near threshold, as a function of q.

The general justification for this class of experiments was discussed by Donnelly and Calarco in the Bates Proposal for a CW Upgrade, Pulse Stretcher Ring, June 1984. This was one of the core experiments listed in that document.

Motivations for pursuing such threshold experiments include the following:

1. It is of interest to study the form of the threshold cross section for virtual as well as for real photons. This requires nuclear transition densities for values of momentum transfer q other than those needed in the photopion reaction and so provides a more stringent test of the entire analysis.
2. If we take, as given, two pieces of information, (a) the nuclear transition densities as determined from analog (e, e') experiments, and (b) the elementary form of the electroproduction amplitude, then we have one other means of introducing q-dependence into the cross section, that is via the spatial distribution of the pion wave function. By measuring the cross section for fixed energy (in the final state CM system), but varying q to obtain a form factor we can, in principle, obtain information on this wave function which would be very difficult to extract in any

other way. This information would, for instance, help in deciding on the correct form of the π-nucleus optical potential at low energies.

3. A study of the π^+ and π^- production between analog states would be particularly interesting in this regard. The π^+ is "pushed out" from the nucleus by the Coulomb interaction, while the π^- is "pulled in", decreasing the effect of the strong interaction in the former case and increasing it in the latter. Thus a comparison provides information on where the strong interaction is effectively switched on and off.

4. As the final-state CM energy is increased away from threshold the production mechanism becomes more complicated than the leading Kroll-Ruderman $\vec{\sigma} \cdot \vec{\epsilon}$ term alone, with new momentum-dependent terms making themselves felt. The ability to vary the kinematic conditions (q, ω, θ'_e) should help in disentangling the various pieces of the production amplitude.

This coincidence experiment provides a continuous curve in the (q,ω)-plane for which the relative energy of the pion-daughter nucleus system (*i.e.*, in the final-state CM frame) is near threshold, in contrast to the (γ, π) reaction where $q = \omega$. In other words, for a continuous range of values of q, there will be corresponding values of ω for which the CM energy will be fixed. In fact for high q, the total energy transferred to the pion-daughter nucleus system may be relatively large even if the relative (CM) energy is nearly zero. For energies near threshold, only s-waves are present in the CM system. When viewed in the lab frame, the pion will still appear to be nearly isotropic; however the residual (daughter) nucleus will have an angular distribution which is sharply peaked about the virtual photon direction $\vec{q}$.

The kinematics just described suggests detecting not the pion (this is difficult anyway at low energies due to its decay lifetime), but the recoiling daughter nucleus in coincidence with the scattered electron. There is a one-to-one relationship between pion angle in the CM frame and residual nucleus kinetic energy in the laboratory frame. A measurement of the residual nucleus energy distribution thus provides a measurement of the pion angular distribution. Any deviation from isotropy in the CM system is then reflected in the energy spectrum of the recoil nucleus; an accurate measurement of this spectrum will thus allow a separation of the p-wave components which become important at larger π-nucleus relative energies. For larger energy transfer and/or lower momentum transfer the recoil cone opens up and the efficiency of recoil detection drops rapidly, until at sufficiently high transferred energies there is no longer any advantage in detecting the recoil nucleus rather than the pion itself.

We can divide the list of possible targets into (a) several special few-body cases: ^{3}He$(e, e't)\pi^+$, ^{3}H$(e, e'\,^3$He$)\pi^-$, and ^{6}Li$(e, e'\,^6$He$)\pi^+$, and (b) heavier nuclei with $A >$

6. Experiments with targets in class (a) may be done, in principle, either with the extracted beam from the SHR or using internal targets in the ring. The large class of targets in (b) will only be possible in the circulating beam of the SHR, owing to the high stopping power of high mass recoils of low kinetic energy.

Our initial proposal to the Bates PAC to study ^{3}He was deferred. The PAC liked the physics and the method of recoil detection, but was skeptical concerning the feasibility of detecting the recoils in the midst of other hadron background at angles of between 35° and 50° relative to the beam, using the SSB telescopes. They chose to defer the proposal pending either measurements or reliable calculations of this background. This is a reasonable request, and we plan to both calculate the background rate and measure it as soon as possible depending upon the Bates running schedule. Our estimates of background would indicate that the hadron induced background is not a problem, as seen in the GR decay experiments. Rather, the problem primarily comes from electron background from Moeller scattering, which can be controlled with a magnetic field between the target and telescope.

Once we have proven feasibility, we will again request time from the PAC and then begin to prepare for the actual experiment. If the SHR schedule is maintained, this experiment could run during the last year of this proposal. This project will provide thesis work for one new student. The detectors and electronics are in hand. The target gas cell for use with the external beam from the SHR would be fabricated at UNH; this would be a simple, low pressure, constant flow device relying on standard wire chamber technology. If it appears to be advantageous to run the experiment with an internal target in the storage ring, we would join a collaboration to build such a target rather than take full responsibility here at UNH, since gas jet targets will be used by many groups.

C.6 The BLAST Physics Program

Our interest in the short range nuclear interaction requires that we study breakup reactions involving many particle final states. In order to identify signatures of particular reaction processes, the reaction space must be characterized in an unbiased way. Separation of response functions provides considerably more information than just the cross section. Polarized beams and targets provide additional control over the contributing currents. A large acceptance spectrometer is required to explore these nuclear degrees of freedom.

Researchers at UNH have been promoting a large acceptance device for the Bates South Hall Ring project for several years. This effort reached a turning point with the presentation of these ideas to the Bates Planning Workshop in June 1989, and the

subsequent identification of the BLAST as the highest priority detector for internal target physics. As Chairman of the newly formed BLAST Steering Committee, one of us (W. Hersman) is now leading a collaboration of over sixty physicists from eleven institutions to develop a conceptual design and a proposal for this device.

The BLAST detector is designed for large acceptance in outgoing particle angle and momentum. The toroidal geometry has a high field near the axis, providing significant curvatures for high momentum particles at small scattering angles, and adequate curvatures for transversely emitted particles. The field on the axis is zero, having no effect on the beam, and allowing small holding fields required for polarized targets. This configuration has an extremely high figure of merit for performing experiments in the following categories:

- Studies of multiparticle emission processes, particularly those for which correlated reaction products must be distinguished from an uncorrelated background.
- Luminosity-limited experiments, particularly experiments with polarized gas targets, where the larger acceptance provides acceptable counting rates.
- Kinematics that are difficult to reach with focussing spectrometers, including reactions emitting particles out of the scattering plane or particles along trajectories close to each other.

The first generation $(e, e'p)$ coincidence program at Bates and other laboratories has already shown that absorption of virtual photons on many-body currents comprises a large fraction of the inelastic continuum. Large acceptance offers the only practical way to define the final state for exclusive studies of multinucleon and nucleon-pion knockout reactions. Because these reactions are likely to produce particles over an extended range of angles and momentum, conventional focussing spectrometers would have to explore the distributions one set of kinematics at a time. Interpretations of experiments, so far, have had to infer the participation of reaction products in unmeasured regions of phase space to test theories on the nature of multi-nucleon absorption. BLAST will provide the capability to cover solid angles approaching 4π, thus providing detailed information on each absorption event. The importance of the multi-nucleon photoabsorption problem was illustrated by the number of recent proposals to study it using BLAST and by the very positive PAC response to the physics.

For experiments with polarized internal gas targets the BLAST detector has great potential. Such experiments have relatively low luminosities (10^{32} to 10^{33} cm^{-2} s^{-1}) and hence are very well matched to the luminosity limitations of a large acceptance detector. This can be easily seen from the recent measurement of spin-dependent quasi-elastic scattering from ^{3}He performed at Bates, experiment 88-02.[47] This experiment was performed with a luminosity of 7×10^{32} cm^{-2}s^{-1}, a target polarization of 25% and

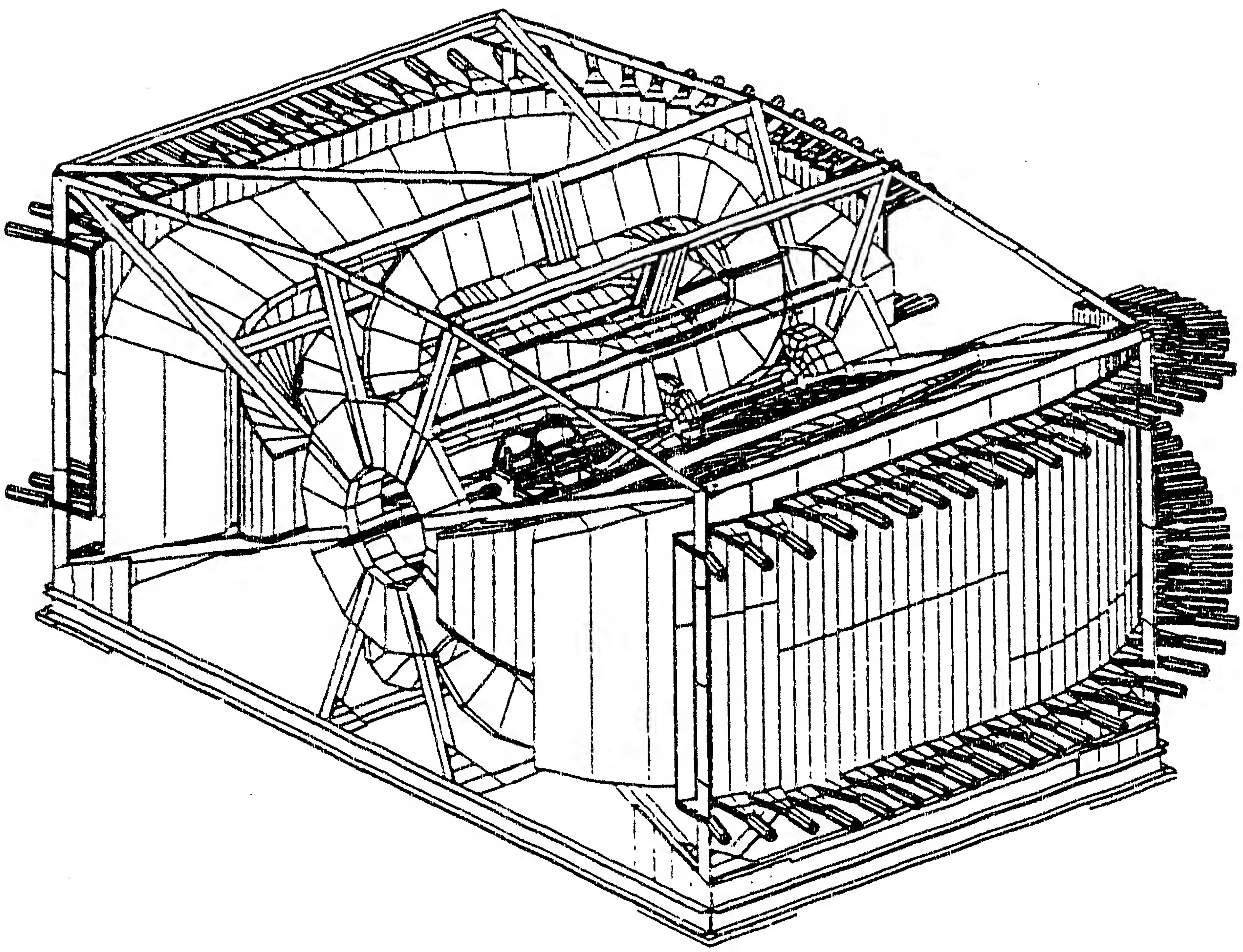

Fig. C.9 The BLAST detector, showing the internal polarized gas ^{3}He target, the detector elements, and the coils and support structure.

a spectrometer with a solid angle of 10 msr and 10% momentum acceptance. With the BLAST Phase 1 detector (80% momentum acceptance, and 1 sr solid angle) and an internal polarized target (50% polarization with more optimal optical pumping), one obtains a very large increase in figure of merit over experiment 88-02. This indicates that the combination of the BLAST detector with a polarized internal gas target in the Bates South Hall Ring will allow a significant advance in the study of nuclei with the electromagnetic probe. The utilization of both spin and coincidence at 100% duty factor in the measurement of electron scattering from the three-body system is unprecedented.

Physics issues addressed by the BLAST program already proposed to the PAC range from nucleon properties to nuclear structure. Studies on polarized helium can reveal properties of the neutron as well as the fundamental N–Δ transition amplitudes. These measurements also address structure questions, including the D-state probability and the occupation of virtual delta resonances in the ground state wave function. Heavier nuclei simulate nuclear matter for exclusive multinucleon photon absorption studies, measurements of nucleon-nucleon correlations, and studies of Δ-nucleon interactions. With a suitable choice of trigger, several different coincidence physics programs on a particular target can be performed simultaneously.

At its February 1990 meeting, the Bates Program Advisory Committee evaluated proposals requesting over 6000 hours of internal target beam time using BLAST. Their response was enthusiastic, "The physics identified in the proposals makes an excellent case for a device with these capabilities. As stated above, PAC strongly endorses the development of internal-target physics at Bates; a large-acceptance detector will play a crucial role in this program." The PAC concluded its endorsement of BLAST as follows: "In conclusion, the committee endorses these research programs, —it i.e. $^3\vec{\mathrm{He}}(\vec{e}, e')$, $A(e, e'x)$, and $A(e, e'\pi)$, proposed for the large-acceptance detector, expecting that a significant fraction of the available beam time will be allotted to such studies. It appears likely that this instrument, properly designed, will become a major component of the physics program of the laboratory."

The UNH group is dedicating a large fraction of its resources into the development of this program. W. Hersman spends almost full time leading this project. Beginning September 1990 he will be on sabbatical at Bates for this purpose. At UNH the development of the Nuclear Instrumentation Laboratory is motivated by the BLAST and CLAS requirements. That effort already requires one postdoc-year and three student-years per year. The group anticipates that direct reactions using large acceptance devices will be the central effort of all group members when the new facilities come on-line.

C.6.1 *Spin-dependent electron scattering from polarized ^3He*

A measurement of spin-dependent electron scattering from ^{3}He using BLAST Phase 1 instrumentation (two of the eight sectors instrumented) will focus on extracting the asymmetries for inclusive scattering, $^3\vec{\mathrm{He}}(\vec{e}, e'p)$ electron-proton coincidences, and $^3\vec{\mathrm{He}}(\vec{e}, e'\pi^{\pm})$ electron-pion coincidences. Next we discuss these three experiments in more detail. It is certain that the physics discussion presented here represents only a fraction of the ultimate potential accessible with the proposed experimental configuration.

Inclusive scattering of electrons from ^{3}He includes quasielastic scattering and extends to the excitation of the $\Delta(1232)$ state in the nucleus. The study of quasielastic scattering is of particular importance since this emphasizes the S-state for which the spin of ^{3}He is carried by the neutron. The asymmetry is expected to be sensitive to the interference of the charge and magnetic form factors of the neutron. In the "dip" region between the quasielastic and delta peaks one expects that the spectrum is dominated by isovector meson-exchange currents which are two-body effects. This region is not well understood in heavier nuclei and a detailed study of the contributions of longitudinal and transverse virtual photons can be made. The measured asymmetry for inclusive scattering at the peak of the delta region should be sensitive to the admixture of D-states in the nucleon. This can be caused by the tensor component in the interaction between quarks and is closely related to the fact that G_E^n is not zero. In addition, in the ^{3}He nucleus, there are possible contributions to the asymmetries in the delta region due to the Δ-nucleon interaction. Thus a measurement of the asymmetries in this region can be related to the properties of the bound Δ-nucleon system.

We plan to measure the asymmetry in electron-proton coincidences $^3\vec{\mathrm{He}}(\vec{e}, e'p)$ scattering. These coincidence measurements can determine the nuclear structure effects that could otherwise contaminate extraction of neutron properties from the inclusive asymmetries. Although most of the asymmetry is attributed to the unpaired neutron as discussed above, important contributions can arise from the small (≈ 1.5 %) polarization of the protons. The proton polarization is induced by small mixed symmetry S$'$ and D-state wave function components.[48] However, their contribution is amplified by the electron-proton cross section and can amount to 50% of the measured asymmetry in inclusive scattering at low transferred momentum. To obtain the neutron form factors one has to correct the measured asymmetries for these effects. The S$'$-state arises from the difference between the n–p and p–p forces. Due to the space-isospin correlation the protons in the ^{3}He nucleus will be aligned. Asymmetries caused by the small S$'$-state components are sensitive to the spatial configuration of the nucleons and therefore may be a precise measure of contributions from three-body forces. The tensor

force will have the effect of aligning the protons opposite to the nuclear spin. The determination of observables connected with the D-state component in the ground state of ^{3}He has been a long-standing few body problem. In this coincidence measurement the spin-dependent momentum distribution of the proton can be mapped out as function of the missing momentum in the range between 0 and 400 MeV/c. The asymmetries at zero missing momentum are sensitive to the mixed symmetry S$'$-state, whereas at high missing momenta the asymmetries are dominated by the contributions from the D-state.

At Stanford, Saclay, and MIT the four elastic form factors of the three-body isospin doublet have been measured up to momentum transfers of 25 fm^{-2}. A conventional theoretical description using only nucleons has been shown[49] to fail in describing the data, i.e. the diffraction minima occur at incorrect positions. A dramatic improvement of the theoretical description occurs when mesons and Δ's are included. It is important to carry out experiments which constrain these non-nucleonic degrees of freedom in ^{3}He. In particular, it would be significant to constrain the probability of a Δ-component in the nuclear ground state, P_Δ. The successful theoretical descriptions of the elastic form factors put this at about 2%. Measurement[50] of the asymmetry in $^3\vec{\mathrm{He}}(\vec{e}, e'\pi^\pm)$ scattering at the $\Delta(1236)$ resonance can probe Δ-components in the ground state of ^{3}He at this level of sensitivity.

Richard Milner and Jo van den Brand, of MIT, are spokesmen for these measurements.

C.6.2 *Multinucleon knockout studies*

In the past ten years evidence has accumulated from a number of experiments at several laboratories that an appreciable portion of the absorption cross section for real and virtual photons and for pions in the region of Δ–resonance excitation involves several nucleons. While some of this multi-nucleon absorption can be understood in terms of initial state and final state interactions, it seems that much of it cannot. There thus appears to be a significant absorption process involving several nucleons in a coherent way. It is possible that such a process is just the short distance limit of initial and final state interactions. However, it is difficult to understand at present why such short distance limiting behavior should involve such large cross sections. We may therefore be seeing qualitatively new physics.

The evidence from pion absorption experiments has mostly come from (π^+, pp) studies, where the two-nucleon component was identified by looking at the energy and angular correlations between the detected protons.[51] A two-nucleon component is clearly seen, but a component corresponding to participation of more than two nucleons

is also seen. Results for a number of experiments on ^{3}He indicate that at and above the Δ-resonance the contribution from three-nucleon absorption is almost as great as that from two-nucleon absorption. For a nucleus as light as ^{3}He this is quite striking. Similar results have been obtained for other nuclei.

While there are considerably fewer data from photon absorption, some of the data raise similar questions. Results from a recent $(e, e'p)$ experiment clearly demonstrate that appreciable ^{12}C$(e, e'p)$ reaction strength exists which involves large excitation energy of the residual nuclear system.[28] Another important observation is that most of this strength appears to be transverse in nature.

Separation of the longitudinal from the transverse response could provide a particularly powerful observable for understanding these processes. The transverse response, dominant at the higher energy transfers, is sensitive to reaction mechanisms including meson exchange currents. At lower energy transfers, however, the longitudinal response is larger. Initial state correlations and final state interactions play a dominant role in this component of the cross section.

It is clear that to make progress in understanding the nature of these medium energy absorption processes one needs a very large solid angle detector. This is not because the event rate is small; in general the absorption cross sections are fairly large. The reason is that it is necessary to characterize as completely as possible the nature of each absorption event. Experiments so far have had to extrapolate over large regions of phase space to obtain information on the nature of multi-nucleon absorption.

Three separate proposals, one of them led by UNH, were submitted to study the problem of multi-nucleon absorption, including targets of ^{3}He, ^{4}He, and ^{16}O. BLAST will provide a nice complement to detectors which are presently under development to study pion absorption with large solid angle. Until we have data from photon and pion absorption using such detectors, we are unlikely to make progress in understanding this potentially crucial problem in medium energy physics.

C.6.3 *Delta-nucleus interactions*

At intermediate energies, the pion-nucleon interaction is dominated by the Δ resulting from a rearrangement of quark spins. The Δ can be created inside the nucleus in the vicinity of another nucleon. Its subsequent propagation is the only way to determine the N-Δ interaction, a quantity as fundamental as the N-N interaction. The principal motivation for studying Δ-nuclear interactions is the attempt to understand the role of baryon internal structure in the strong interaction. That is, by studying the interaction of different baryons with each other, we hope to gain insight into the importance of various degrees of freedom in determining the nuclear force and thus to guide

the construction of models for the study of strong interaction dynamics.[52] Understanding nucleon-nucleon correlations in nuclei will also depend upon our understanding of the role played by nucleon resonances in nuclei.[53]

To study Δ-nuclear interactions, we must form the Δ in the presence of other nucleons. The pion and the photon (real or virtual) provide complementary probes. The comparison of pion and photon absorption data is of considerable interest. The initial state couplings are different, leading to different spin dependence. Also the geometrical constraints are different. The photon sees the entire nuclear volume and can create an unstable particle, like the Δ, in the very center of nucleus, making possible the study of interactions in the final state. Pions, on the other hand, interact so strongly that whatever process they encounter is likely to originate in nucleons in the low-density nuclear surface. The essential element is that the same physics is being probed in studying Δ propagation after formation with either probe.

The UNH group led a proposal to the PAC to measure the dependence of the $(e, e'p\pi)$ cross section on various kinematic parameters such as the invariant mass, the four momentum transfer of the photon, the recoil momentum, the proton emission angle and the π emission angle using BLAST. Since the relevant information is contained in the final state interaction, a study over several nuclei is required. Complete studies of $\mathrm{D}(e, e'p\pi^-)$, $^3\mathrm{He}(e, e'p\pi^{\pm,0})$, $^4\mathrm{He}(e, e'p\pi^{\pm})$, and $^{16}\mathrm{O}(e, e'p\pi^{\pm})$ are planned.

C.6.4 *Spin-dependent electron scattering from polarized deuterium*

This proposal is in the development stages and will be proposed at the next Bates PAC. With the emergence of new technologies for producing polarized electron beams and polarized nuclear targets, the hope of separating the individual multipole hadronic current matrix elements may finally be realized. Two technologies are being pursued for producing polarized deuterium: an optically-pumped spin exchange technique, under development at Argonne; and a high density atomic beam, being developed at Wisconsin. We propose under separate cover a program to optimize and adapt the Argonne target for use in the Bates SHR with BLAST. Here we discuss briefly the physics motivation of the measurements.

Frankfurt and Strikman point out that one of the crucial questions regarding deuteron structure remains the s- and d-state contributions as a function of momentum transfer.[54] Polarization of the target would result in spin dependence of the response of the d-state. Although elastic scattering from tensor polarized deuterons determines the coherent quadrupole moment, the incoherent knockout response allows mapping the momentum distributions of nucleons in these orbital states. Of particular interest is the possibility of a minimum and sign change in the s-wave amplitude, and the dominance of the d-wave above initial momentum 300 MeV/c.

The average properties of the Δ-nucleon interaction are known, parametrized as an optical potential, due to the final state distortions in the delta production channel of pion and photon reactions. The microscopic contributions to the various channels have not been isolated. Quark models predict a strongly repulsive nucleon-delta interaction in the S=1, T=1 channel.[56] Response functions that are time-reversal odd vanish in the plane wave approximation. These response functions have non-zero contributions from overlapping resonances or final state interactions.[57] The clean separation of multipoles in the spin response will provide the best access to the nature of this fundamental interaction.

While the deuteron electromagnetic response functions provide the observables, certain kinematic regions of the reaction are sensitive primarily to the properties of the constituents. In particular, studies of the deuteron offer the only way to access the higher momentum transfer structure of the neutron.[58] A complete study of the deuteron will provide the most direct information possible of the static properties and transition amplitudes of the neutron.

We plan to propose an experimental determination of the electrodisintegration multipole matrix elements of the deuteron using the Bates SHR and the BLAST. In addition, pion electroproduction from the deuteron will constrain the transition matrix elements of the neutron, test for modification of the proton transition matrix elements, and characterize the components of the nucleon-delta interaction in the final state. All reactions will be measured over the full kinematic range accessible to a 1 GeV incident electron beam. The complete set of polarization observables will be characterized, including the dependence on beam, target, and, potentially, the outgoing nucleon polarization. The proposed experimental facility will simultaneously measure the complete range of electron inelasticity, including elastic scattering, threshold breakup, quasi-elastic breakup, and pion and resonance production. The measurements will provide an overdetermined set of measurements, and be performed simultaneously with calibration measurements. No other measurement technique, existing or planned, can provide a similarly complete description of the proton in the medium, neutron, and deuteron.

C.7 The CLAS Program

We intend to extend our study of many-body currents in nuclei to shorter range and higher energies using the CEBAF Large Acceptance Spectrometer (CLAS) in Hall B. We have submitted a proposal to PAC4 to perform electron induced multinucleon knockout reaction measurements. Seven similar proposals by other groups were submitted with similar objectives. The PAC response was very supportive. "The PAC believes that the capabilities of the CLAS are ideal for survey experiments of this type." They

recommended that the initial measurements be carried out on "^{3}He and one heavy nucleus", and that the separate "proponents should attempt to coordinate beam energies, targets, and data acquisition, so that the experiments can run simultaneously."

A Physics Working Group was formed consisting of the membership of these physics proposals. The membership elected one of us (W. Hersman) to chair the working group, and serve as the group's representative to the Coordinating Committee of the Hall B Collaboration. The process of merging the objectives into a single effort began at two working group meetings, held recently at the CEBAF User's Group Meeting, and at the PANIC conference at MIT.

We are committed to contributing to the CLAS instrumentation as well. We have submitted a Memorandum of Understanding to the CEBAF management to develop low scattering wire chamber gases, perform fast scintillator prototype development, and participate in fabricating the time-of-flight system. The University partially renovated laboratory space for our Nuclear Instrumentation Laboratory. A supplemental grant from DOE supplied six scintillators and photomultiplier tubes, and data acquisition instruments. Lynette Gelinas completed an Undergraduate Research Project, internally funded by UNH, to design and construct a Čerenkov detector mirror. Tests will begin shortly. We presently have one student funded by the Army, Jyuji Hewitt, working on a Master's Thesis on wire chamber instrumentation, aided by a summer student. He will characterize low-mass drift gas properties, including behavior in a magnetic field. Fulfilling our entire MOU commitment to CLAS requires additional resources, requested under separate cover.

The CLAS collaboration has requested that the physics working groups should contribute Monte Carlo routines simulating their experiments. We have developed a versatile multiparticle emission Monte Carlo routine. Mark Leuschner has written and tested the code using a variety of reactions, detector geometries, and acceptances. We plan to supply this code to the CLAS collaboration and the multiparticle emission working group.

We have developed original algorithms for performing data analysis of multidimensional data, a necessary requirement for the CLAS. The technique can extract response functions with sensitive dependences of kinematic parameters without binning and with no loss of precision. Mark Leuschner has coded the algorithm and is presently testing it with the Monte Carlo routines. We plan to publish the results when we complete the tests.

The CLAS will begin to produce data in 1996. Nevertheless, a substantial commitment of manpower on the part of user groups is required immediately. Our investment of student, postdoc, and faculty time, already begun two years ago and continually

growing, is a benefit to that project and to our program. Over the proposed contract period, we plan to devote an average of one-postdoc year and two student-years per year to instrumentation development. An instrumentation proposal under separate cover requests resources to double that effort. This involvement lends diversity, balance, and future direction to our program. These benefits offset possible restrictions or delays that our other activities may experience.

C.8 Other CEBAF Involvement

We have also been active in other CEBAF projects. John Calarco has been asked to join an effort to design the trigger logic for the Hall A spectrometers in collaboration with Mike Finn of William and Mary. This is a result of our experience with coincidence electronics, previously solicited for the MIT-Bates knockout studies, and, more recently, with compact ECL networks in the course of our giant resonance work.

This commitment of time to the CEBAF Hall A electronics design will be beneficial to our other work. We have also committed ourselves to the design and development of the trigger logic for the BLAST, which will be of a much larger scale, but which will be based on the same basic set of hardware modules. In addition to part of John Calarco's time spent on the project, we will also involve part of the time of one student and one postdoc in order to familiarize them with the appropriate hardware and software.

Section D

HIGH RESOLUTION NUCLEAR STRUCTURE WORK

Over the past decade, high resolution electron scattering experiments have been the backbone of our research program. Our experimental results have contributed to advance our understanding of low lying nuclear structure and they still provide a stimulus to improve theoretical models.

Over the past fifteen years a significant body of data has been collected and the interest and commitment at the major labs to continue such experiments as their prime activity has declined. This has led to a situation where it has been very difficult to obtain beamtime even for approved experiments that had fairly high ratings. Our research group has adjusted to this new situation by shifting the main focus of our activity to multi-particle coincidence experiments. Nevertheless, we intend to continue our high resolution nuclear structure program at a low level with respect to manpower commitment. In addition, a significant part of our interest in this field has shifted to the interpretation of the large body of data, as we feel that any additional experiments require very strong motivation from the nuclear structure theory.

Experimental results from electron scattering during the last decade have demonstrated clearly the limitations of the mean field approach to nuclear structure. It has become clear that the nucleus is a highly correlated system which affects all the observables. This was demonstrated by ground state charge distributions as compared to Hartree-Fock (HF) predictions, by the lack of strength in high spin magnetic transitions, or the need for effective charge. While this was well accepted for nuclei away from closed shells, it has now become apparent also for spherical or doubly closed shell nuclei. The questions that remain are again of quantitative nature where electron scattering experiments are superior to any other probe. Some of these are:

1. What are these occupations around the fermi level?
2. Single particle and collective degrees of freedom are strongly mixed. What is the nuclear dynamics?

3. All ground state correlations suggest a transformation to "generalized quasi-particles." What is the nature of these quasi-particles?
4. Nuclear dynamics: How does fragmentation of single particle strength in odd-even nuclei affect (high-spin) states in even-even nuclei built on these single particles?
5. Do non-nuclear degrees of freedom have any measurable effect on observables in low energy nuclear structure?

With our experiments we hope to contribute to the answers of these questions.

In section D.1 we will discuss the status of the experiments done in the last few years. We then describe the achievements in nuclear model calculations in section D.2, and in section D.3, we discuss the program of activities for the period of this proposal.

D.1 Experimental Status

D.1.1 *Measurement of the form factor of the* 0_2^+ *level in* ^{48}Ca.

Data taken at Bates[59] measuring the 0_2^+ transition charge density in ^{40}Ca have shown that shell model calculations must have very large bases, including components from the proton s-d shell in order to adequately describe the measured densities. Shell model calculations[60] in fact show that the excited 0^+ states in the calcium isotopes have large admixtures of 2p-2h, 4p-4h and even 8p-8h components in their structure. The purpose of this experiment was to measure the form factor for the weak 0_2^+ excitation at 4.284 MeV in ^{48}Ca to obtain information on these core components as the neutron number was increased in the $f_{7/2}$ orbit.

Data taken in January and May 1989 at 250 and 360 MeV covering twelve momentum transfer points from $0.69 \leq q \leq 2.25 fm^{-1}$ have now been analyzed. Additional high-momentum transfer data from the 1979 Bates experiment on ^{48}Ca have been re-analyzed to provide upper limits to the cross section. These additional data, when combined with the low momentum transfer data from Darmstadt[61] have allowed an extraction of the transition charge density in a Gauss-Polynomial expansion.

Fig. D.1 shows the form factor and extracted densities for the second monopole excitation in ^{40}Ca (left) and in ^{48}Ca (right). A fit was performed in a Gauss-Polynomial expansion for the ^{40}Ca data. Then the ^{48}Ca data were fit, using the same radius parameter (2.295 fm) found from the ^{40}Ca fit. The extracted densities, though similar in shape, have clear differences in their magnitude at the origin and at the second maximum around 3.0 fm. In the bottom figure is shown the subtracted charge density difference between the two excitations, which displays this more clearly. Excess strength at the origin may be due to increased participation from protons from the $2s_{1/2}$ orbit.

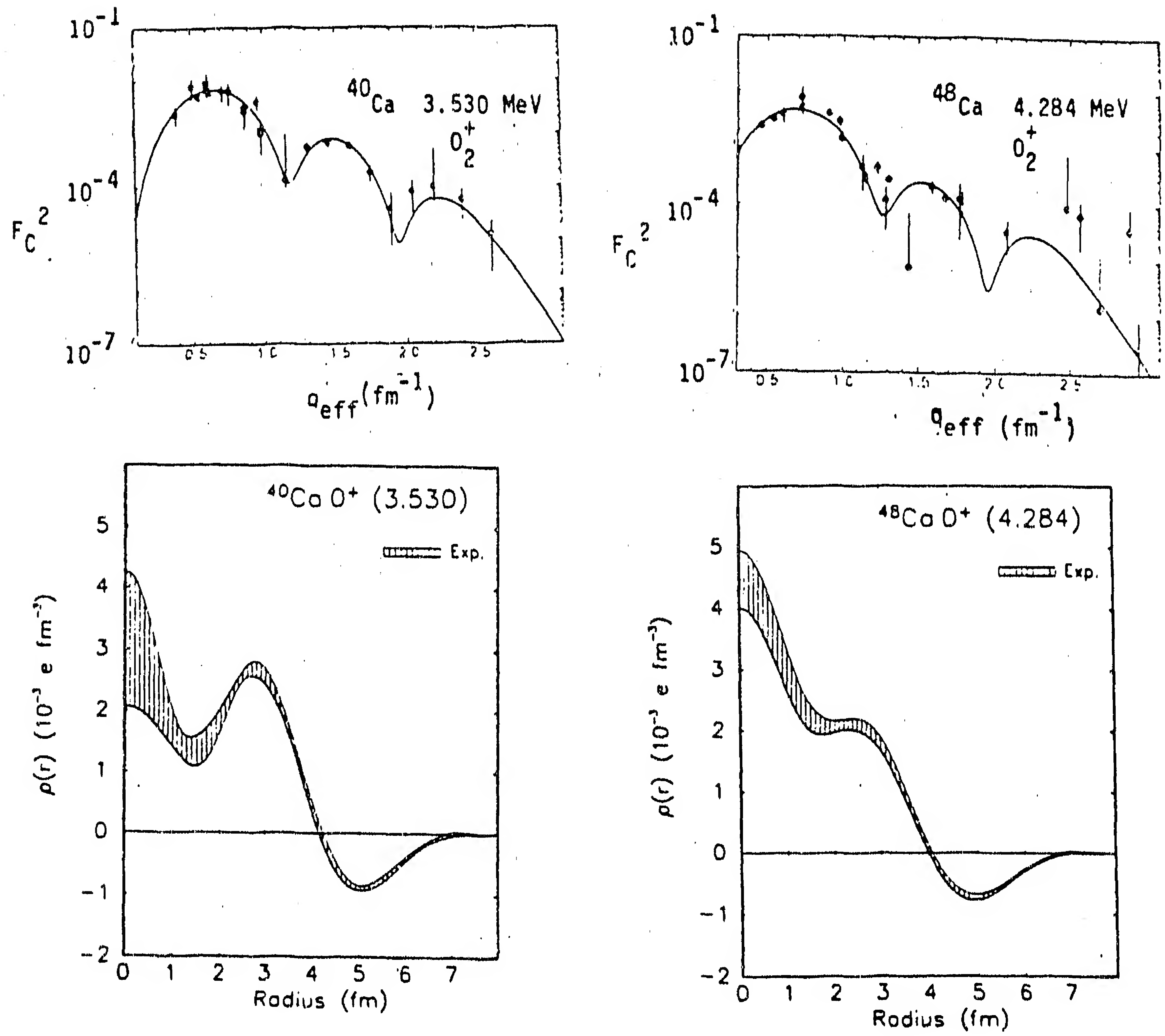

Fig. D.1 Cross-sections for the first $E0$ excitation in ^{40}Ca and ^{48}Ca. The lower part shows the extracted transition charge densities.

Calculations based upon the coexistence model of Gerace are in progress and should be completed by the end of 1990.

D.1.2 *The N=50 nuclei.*

We have completed our experiments for these nuclei with the 180° backward scattering experiment from ^{89}Y. This series of experiments on ^{86,87,88}Sr, ^{89}Y, ^{90}Zr, and ^{92}Mo has been a rich field for nuclear structure. Our paper[62] on the results from ^{92}Mo has recently been published. Our papers on core polarization in ^{86}Sr (J. Connelly, *et al.*.) and a second on the single particle excitations in ^{89}Y have been accepted for publication in *Phys. Rev. C.* We will now briefly summarize some of the results.

We have learned that the strength of the 8^+ excitations in the even-even nuclei is probably the most direct information on the occupation of the proton $1g_{9/2}$ orbit in the nuclear ground state. This comes about as the excitation mechanism is a breakup of a proton pair $(1g_{9/2})^2_{0^+} \rightarrow (1g_{9/2})^2_{8^+}$. Realistic model calculations have shown that core polarization contributes to the strength only at the few percent level and can be accounted for. Such a small core polarization contribution is also supported by our experimental results from ^{86}Sr. This strength can be translated into occupations by using the comparison to predicted strengths in realistic large scale shell model calculations.

Measurements of the longitudinal and transverse strength of the E5 excitations in ^{89}Y, ^{90}Zr, and ^{92}Mo allow us to relate the $2p_{1/2}$ proton occupation to that of the $1g_{9/2}$ occupation in these nuclei. This has been discussed in our papers[62,63] on ^{92}Mo and ^{90}Zr. A paper contrasting the various experimental results on these occupations within the framework of the realistic model calculations is in preparation. This includes the results from inelastic scattering as well as the knockout reactions $(e, e'p)$ or transfer experiments. The same E5 transitions mentioned above have demonstrated very clearly how ground state partial occupations contribute to the observed quenching of the transverse scattering amplitude from even-even nuclei.

Our experiments on ^{89}Y have demonstrated the strong mixing of single particle and collective degrees of freedom. Through this mixing the single particle aspect is reduced (quenched) while the loss in transition strength is compensated for by core polarization representing the collective degrees of freedom. In ^{89}Y the reduced single particle aspect is seen in the quenched transverse strength and for the charge operator in the reduced strength of the interior lobe of the transition density. This observation has led to an investigation of the $2p_{3/2} \rightarrow 2p_{1/2}$ proton transition in various nuclei that will be discussed below.

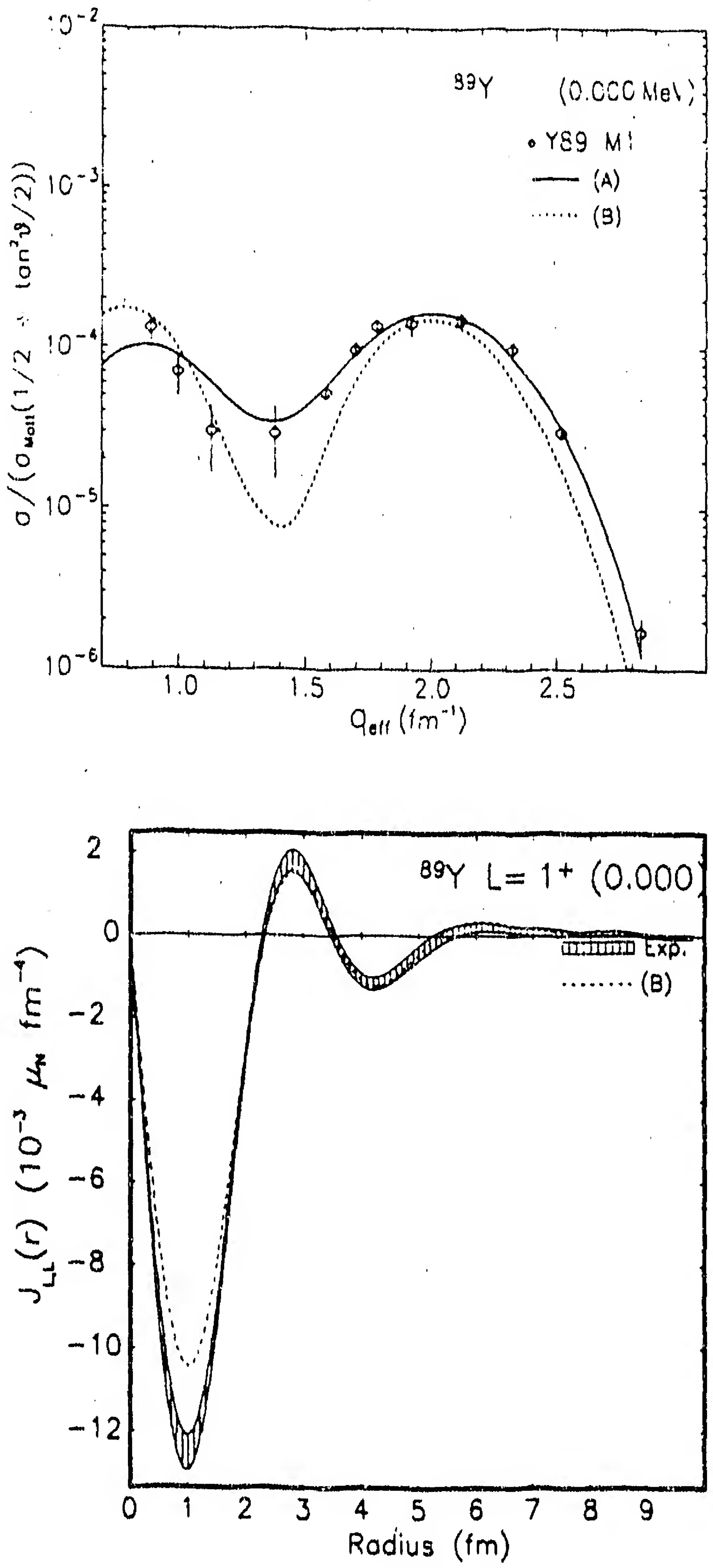

Fig. D.2 Form factor for the ground state M1 distribution in ^{89}Y. The solid line is the bets fit, the broken line is the effective operator prediction. The top shows the cross sections, the bottom shows the densities.

The M1 ground state scattering from ^{89}Y has shown fairly strong contributions from core polarization. This experiment is complete, and we are working on a paper summarizing the results. The experimental data and the prediction using the single particle picture (a) and using the effective operator approach is shown in Fig. D.2.

D.1.3 *Proton $2p_{3/2} \rightarrow 2p_{1/2}$ transition*

The double hump feature of the transition charge density for the $2p_{3/2} \rightarrow 2p_{1/2}$ transition is very special for the fp-shell. It allows to separate the single particle contribution in the transition from the core polarization part, whereas the transverse density is essentially all single particle contribution. As such it allows us to determine the size of the mixing between single particle and collective degrees of freedom. In addition, the quenching between the single particle part in the transition charge and the quenching in the transverse part are different and indicative of the ground state correlations.

We have measured two transitions namely the ones in ^{65}Cu and in ^{71}Ga. The experiment on ^{65}Cu is fairly complete. Data in forward direction and the large momentum transfer data in backward direction were taken at NIKHEF. The low momentum transfer 180° scattering was recently done at Urbana, Ill. Together with some published data at 165° from Darmstadt, a fairly complete analysis of the data on ^{65}Cu is possible. Preliminary densities extracted from this experiment are shown in Fig. D.3.

The experiment on ^{71}Ga is less complete. The results so far have been quite surprising. Whereas the transverse part in this transition appears as strong as in ^{65}Cu, the longitudinal part is reduced by about two orders of magnitude. We interpret this as an almost complete cancellation of the longitudinal scattering due to ground state correlations.

D.1.4 *Electron scattering from ^{118}Sn*

The data taking from this experiment has been completed. Forward angle data have been taken covering a momentum transfer region of $1.1 \leq q \leq 2.75$ fm^{-1}. With low-q data from NIKHEF, this should allow the mapping of the transition charge density for low-lying excitations. Backward angle data were taken at 155° scattering angle over a momentum transfer region of 1.0 to 2.1 fm^{-1}. These back angle data will allow the identification of high spin neutron excitation expected in the vicinity of 3.0 MeV region.

The forward data have been analyzed for excitation energies up to 4 MeV. The backward data have not been analyzed yet. Extracted densities for the first 2^+ excitation and evidence for the possible existence of a high-spin neutron excitation at 3.5

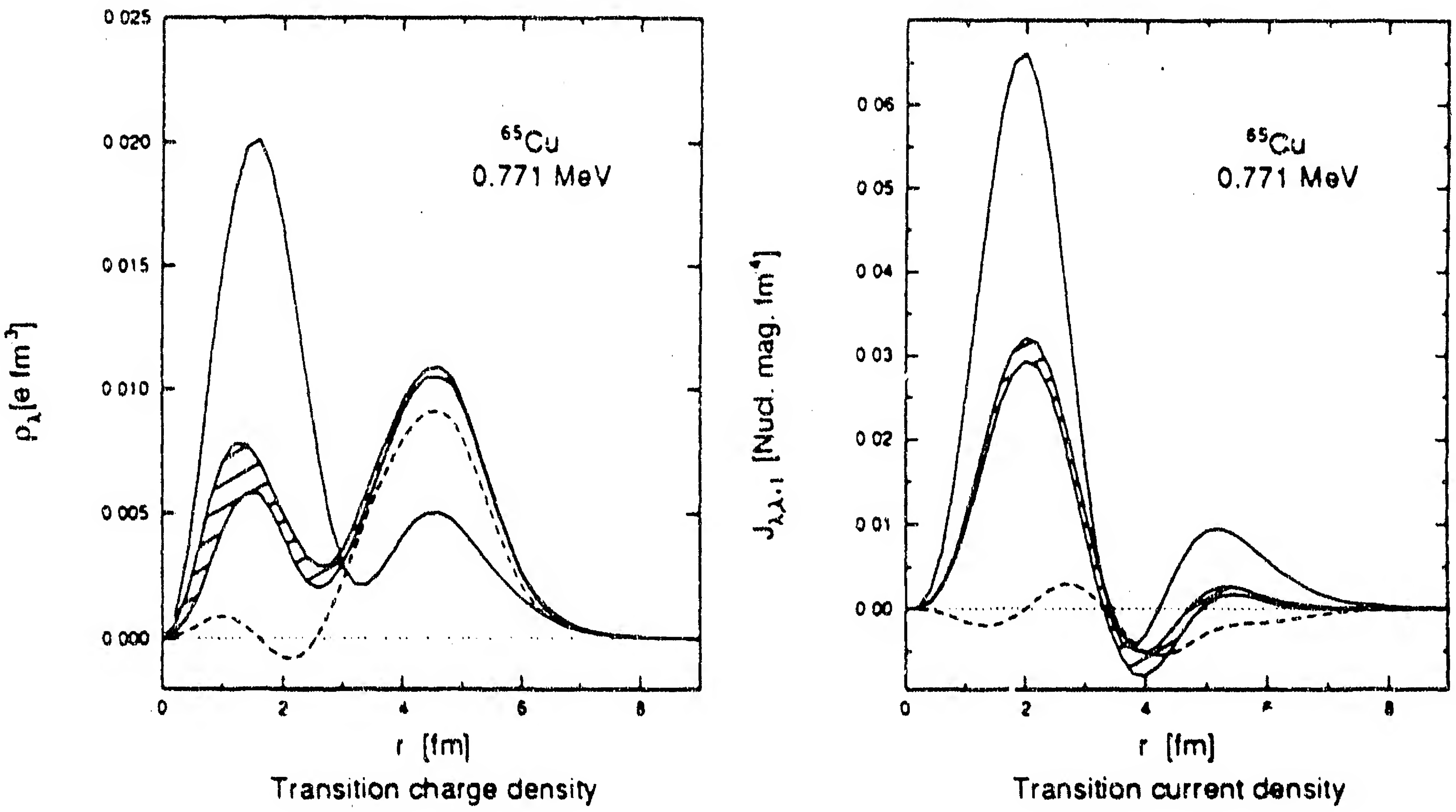

Fig. D.3 Transition charge and current densities for the first inelastic transition in ^{65}Cu.

MeV excitation were presented at the May, 1989 general meeting of the APS. John Wise, who has been responsible for this analysis is leaving us. J. Meng, a new graduate student in our group will take this analysis over from John, so that it can be completed.

The tin-isotopes are the counterpart to the N=50 nuclei. For tin, the protons form a closed shell, and the shell model calculations will be done for the valence neutrons only. In this description, all of the observed transition charge densities are due to core polarization. Thus we can test the ability of the calculation to predict the proper amount of core polarization.

D.1.5 *The Ce-isotopes*

The experiment has been restricted to ^{140}Ce and ^{142}Ce. Data have been taken mostly in forward direction in the momentum transfer range $0.5 \leq q \leq 2.5$ fm^{-1}. All the data have been analyzed, and transition densities have been extracted for most of the levels observed below 3.4 MeV.

For ^{140}Ce we plan to do shell model calculations. As the neutrons form a closed shell, the size of the basis can be handled by present computer codes. For ^{142}Ce the extra two neutrons bring this nucleus out of the reach of present shell model codes. For this nucleus a fairly powerful description has been the quasiparticle-phonon approach. As a first step, phonons are being generated using the RPA formalism. In a second step one-phonon and two-phonon states are coupled together using the residual interaction. The calculations are being done by V. Yu. Ponomarev from the Joint Institute for Nuclear Physics in Dubna and by A. P. Platonov and E. E. Saperstein from Moscow. A publication is in preparation.

Two data points have been taken at backward angles to search for high spin stretched states and study their quenching and fragmentation. Analysis focusing on the high spin states[64] has identified an M12 state of 6.31 MeV in ^{140}Ce, with a strength only 8% of that expected from the extreme single particle model. Its lack of strength and the fact that all other other candidates for high spin transitions are still weaker suggest that the quenching and fragmentation mechanisms previously observed in the lead region are also operative in ^{140}Ce. Similar remarks apply to ^{142}Ce for which no high spin states have yet been observed in our analysis.

D.1.6 ^{208}Pb

We have taken high resolution data from ^{208}Pb in the momentum transfer range of 0.5 to 2.8 fm^{-1} in forward scattering and 1.0 to 2.9 fm^{-1} at the backward scattering angle of 155°. The resolution was ≤ 20 keV. Cross sections have been extracted for over 120 inelastic levels and a Distorted Wave Born Approximation(DWBA) analysis was performed for over 50 of these excitations below 7.4 MeV. Spin and parity assignments have been made on several states, particularly those which may be dominated by only one particle-hole configuration.

The quenching of the transverse form factors of the 14^- and 12^- excitations in ^{208}Pb seen by Lichtenstadt, *et al.*[65] has been verified in this experiment. However, the amount of quenching, in particular for the 12^- state at 7.068 MeV, is greater than the 50% reported by Lichtenstadt. We also see evidence of strong fragmentation of the 12^- strength into a neighboring level unresolved by the Lichtenstadt experiment. Several other high spin states ($J^\pi = 11^+$, 10^-, 9^-, 9^+, 8^-) have been observed and all are quenched to 40% to 60% of the predicted single particle-hole form factors.[66]

The energy regime below 4.8 MeV excitation energy is quite interesting since we now have identified and extracted transition densities for nearly all of the states predicted by mean field theories. This regime includes both electric and magnetic states with low multipolarities and negative parity. These excitations are due to transitions of nucleons from just below to just above the fermi level. A complete data set in this energy regime will place several restrictions on theoretical calculations.

This experiment was the Ph.D. thesis topic for J. Connelly, who graduated in May, 1989. While the data collection for this experiment is complete and the above results are the subjects of two publications in preparation, there remains a wealth of information in our cross section data base that has yet to be mined. We continue to work with Jim on this project to further sift and systematize the results of this experiment. Presently we are obtaining some model calculations that will help us in the interpretation of the data.

D.2 Shell Model and Core Polarization Calculations

Shell model calculations have been very successful in the quantitative description of low lying nuclear levels; certainly as far as the level energies are considered. However, when it comes to the calculation of one- or two-body densities the results are much less satisfactory. The main problem being that the predicted strength contained in the shell model sub-space usually is 25% or less than the observed strength. More recently, attempts have been made to account for core polarization t! ugh semi-microscopic

models. In these, core polarization is being calculated via some interaction that is seemingly unrelated to the interaction within the valence space.

To put the whole procedure on a more solid footing, we have developed a selfconsistent theoretical approach that ties together the calculation of the energies and the calculation of the one-body densities. In our approach of the Operator Renormalization Approximation for Shell Models (ORASM) we compensate for the truncation of the full space to the valence space by a rotation R of the basis within the full Hilbert space. This rotation can be calculated applying the Hartree-Fock principle. Through this, all operators change in the same way to

$$O^{\rm eff} = R^{\dagger}\, O\, R$$

including the hamiltonian. Whereas it has been customary to fit the result of this rotation for the hamiltonian $H^{\rm eff}$, we are fitting the effective interaction that creates the necessary rotation R. Once R is determined, it allows us to calculate the effective hamiltonian on the same footing as the effective one-body densities.

The formulation is derived from basic principles and can be carried through to all orders. In our application we found it sufficient to carry the expansions through to first order, except for a few places where we included some second order terms. A paper that describes the technique and gives the results for the N=50 nuclei is in preparation.

The computer program that carries through these renormalizations for all operators has been developed for running on the PRIME 6550 and has now been modified to run under UNIX on the DEC-workstations. We have carried out explicit calculations for the N=50 nuclei and have fitted an empirical interaction that reproduces energy levels better than the fit by Ji and Wildenthal.[67]

During the past year we have improved these calculations considerably. An important improvement came about by including more of the exchange terms that lead to the quenching of the single particle strength. These affect both, the effective shell model potential and the effective one-body densities.

The second improvement came from the search for an interaction that would improve the description of these nuclei. This interaction has a small density dependent part that was left fixed. In addition, eight coupling constants that describe the interaction have been adjusted. It should be noted that the results are insensitive to certain combinations of parameters. This can be understood as in the limit of zero range, an interaction of the form

$$V_o\,(3 + \tau\tau'\sigma\sigma')$$

or

$$V_o\ (2 + \tau\tau' + \sigma\sigma')$$

vanishes exactly if exchange terms are included. Thus these combinations give contributions only to the extent that the interaction is of finite range, which leads to very small contributions for the mass 4.0 fm^{-1} mesons. Thus the calculations are sensitive to essentially six parameters or less.

The agreement in the predicted energy levels is typically 100 keV. There are only a few levels for which the discrepancy is larger. It should be noted that fitting these six parameters yields nuclear energy levels that give as good an agreement with the observed levels as the fit of Ji and Wildenthal[67] where some 30 parameters were adjusted. In addition, the densities calculated with our ORASM formulation that require no additional parameters or effective charges give a much more realistic description of the observed densities as those of Ji and Wildenthal.[68]

In our calculations the strength of the collective transitions agree typically to within 5% with experimental values. For the weaker transitions where significant cancellations occur somewhat larger discrepancies have been found. Particularly good agreement has been found in the transverse densities. This includes both, the transverse electric density and the magnetic transitions. Here the agreement is almost quantitative. Preliminary results have been presented at conferences and have appeared in proceedings.

A recent development has been the inclusion of predictions for transfer or knock-out reactions such as $(e, e'p)$ or (d, p), $(^3He, d)$, etc... The single particle removal operator is renormalized by the same dynamics that is quenching the transverse strength. Explicitly calculating these renormalizations will allow us to make connections to other experimental results and describe these on the same footing.

With the considerable success in predicting the charge densities for these states, we will use these wave functions to predict the densities that determine the proton scattering cross section. In collaboration with J. Kelly from the University of Maryland we will use these predictions to help us understand the proton scattering results on these nuclei.

The reliability of a theoretical description can be judged only based on a broad agreement between prediction and observed properties and not only on the prediction of a single nuclear level. This distinguishes our treatment of the M1 excitation in ^{88}Sr from that of Weise. In Fig. D.4 we contrast the interpretation of Weise for this state with our prediction. Weise needed strong $\Delta - h$ components in the wave function in order to explain the quenching in the (e, e') cross section. In our calculation, the prediction with core-polarization alone not including exchange currents and not including $\Delta - h$

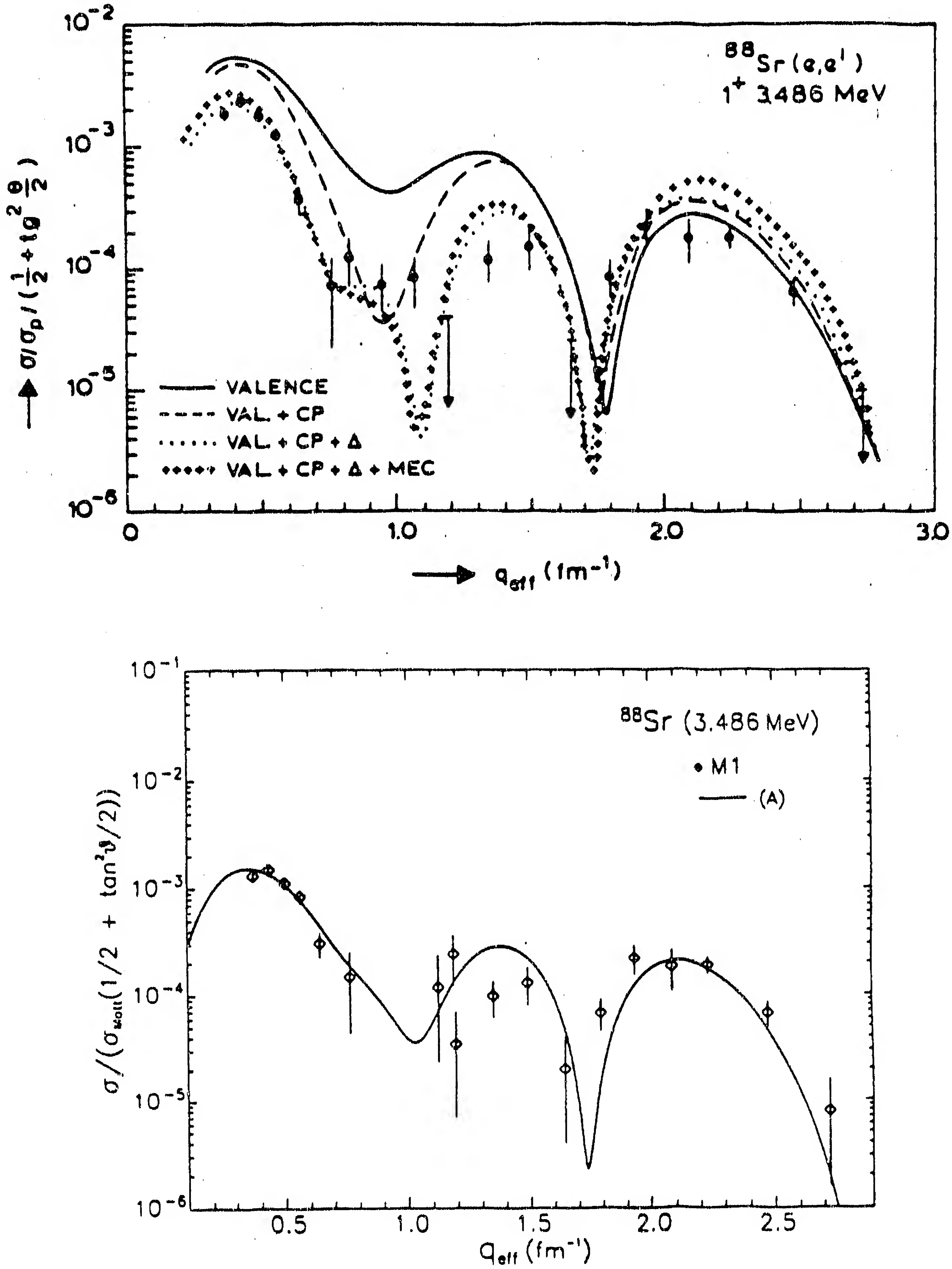

Fig. D.4 Top: Interpretation of Weise for the M1-excitation in ^{88}Sr; bottom: Present calculation with nuclear degrees of freedom only.

components gives already a good description of the observed data. In our calculations the quenching is mainly produced through deoccupation of the orbits and a strong backward (hp) component in the transition due to ground state correlations.

D.3 Future Developments

We will continue to work in this field but with reduced manpower. Typically, we expect that about 60% of the research time of J. Heisenberg, 20% of one post-doc, and one full time graduate student will go towards the continued development in this area.

We expect to get beamtime for the approved experiment on ^{138}Ba by late 1990 or early 1991. One of us is also collaborating with M. Manley on electron scattering from ^{23}Na and ^{21}Ne. As we found that quite unexpected new results have been found in odd-even nuclei, we may push for some new measurements on the nuclei ^{117}Sn, ^{139}La, and ^{141}Pr and submit proposals on this to the Bates accelerator as time and manpower commitments allow. Odd-even nuclei display quite different features than the neighboring even-even nuclei; and with their closed proton or neutron shell structure these nuclei fit well into our program for the development of numerical calculations.

The present work of large scale shell model calculations has been extended to the Ni-isotopes and to the Sn-isotopes. In both cases the valence space consists of neutrons only. The experimental electron scattering data test directly the quality of the core polarization calculation. As the calculations for Sn require a considerably larger basis, we have performed only a single calculation for Sn so far to demonstrate the feasibility of these calculations. As the computation time is more than double that for the N=50 region, we have decided to first work in the Ni-region before applying it to the Sn-region or even performing an elaborate search. However, with a good interaction now being available for the N=50 nuclei, we expect that we can apply this interaction to the Sn-region without the need for extensive adjustments.

Similarly, we will be able to carry out calculations for the nuclei ^{140}Ce and ^{138}Ba. The electron scattering experiment on ^{140}Ce has been completed, whereas the experiment on ^{138}Ba has been approved but not yet run. Our expectation for these nuclei is that again one needs only minor modifications of the interaction in order to get as good agreement as in the N=50 cases.

Presently our program has been tested only in cases where the shell model calculation is done in a space either containing protons only or containing neutrons only. While this is not a limitation of the formalism itself, the programming has not yet been tested to the same level for the mixed proton-neutron case. We intend to start working on this aspect. This development is also essential for the interpretation of our

experiment on ^{65}Cu. Once this feature has been tested, we will be in the position to apply this technique to the sd-shell nuclei.

The basic approach in our calculation starts with the HF-principle that has been applied to generate all ground state correlations. As such it can be applied to doubly closed shell nuclei as well. To test these results we plan to calculate excited states via a TDA calculation from the correlated ground state. The programs for this approach have been generated but not yet thoroughly tested. With the new computational resources available, we now expect to get first results on ^{208}Pb within a few months. These calculations are intended as a guide in the interpretation of our (e, e') data from that nucleus.

The speed of progress in data interpretation, previously limited by computer power, has recently increased. With the acquisition this month of three RISC based DEC workstations through a generous supplement from the DOE, our computational resources have increased many-fold. Single calculations that used to require days, now take hours.

Section E

THEORETICAL STUDIES

New experimental facilities, such as CEBAF and Bates, are designed to explore the nucleus in regions of large momentum transfers and extreme conditions. The nuclear physics group at UNH plans to participate in experiments which will use the new facilities at CEBAF and at Bates to study electromagnetic reaction mechanisms and two-nucleon correlations. It is questionable that existing theories of nuclear matter are adequate to treat electromagnetic interactions with nucleonic constituents at high energies and momentum transfers.

The relativistic field theory models that have been called quantum hadrodynamics[69] (QHD) have shown considerable promise of a reasonable compromise between QCD, the apparently correct theory of nucleonic matter, and the older non-relativistic models, which do not contain mesonic degrees of freedom. QHD treats nucleons as point fermions with Yukawa interactions. It assumes that the most important part of QCD to preserve is the intermediate range attraction caused by double quark-antiquark exchange. This is represented by a scalar (σ) meson. Short range repulsion is modeled by a vector (ω) meson. Lagrangians for these theories contain bare masses and coupling constants for all the particles.

QHD calculations have emphasized self-consistency and preservation of general conservation laws such as Lorentz covariance, gauge invariance, and causality. At the mean-field level, the σ-ω model (QHD-I) has provided a relativistic mechanism of nuclear saturation and correctly predicts the shell model spin-orbit interaction. Calculations for finite nuclei have successfully described the ground state rms radii, charge densities, neutron densities, quadrupole deformations, and provide densities for calculations of elastic proton-nucleus scattering.

QHD calculations can be carried out at several levels of approximation. At the mean-field level, the theory takes into account negative energy states by filling them up. The relativistic Hartree approximation includes explicitly the one-loop vacuum polarization diagrams. Recently, vacuum renormalization corrections for QHD-I have been calculated up to and including the two-loop diagrams.[70] These two-loop terms

turned out to be large corrections to the one-loop results — which means that either the loop expansion is not a useful one to use, or it signals a fundamental difficulty with the underlying theory.

John Dawson has been working with relativistic field theory models, in collaboration with others, and has been a regular visitor at the Nuclear Theory Center at Indiana University. Since our group at UNH has been involved in measuring single-particle charge and current transition densities, our first work in this field were to calculate mean-field theory relativistic wave functions and single-particle current operators. This led to a more detailed description of the mean-field theory, and we worked on a relativistic Hartree-Fock theory and developed computer codes for that theory. These codes are now operational. We have also become interested in nuclear excitation models at the mean-field theory level, and have developed and submitted for publication[71] the simplest of these models, the relativistic RPA model for iso-scalar modes.

On the basis of these results, we propose to extend the RPA calculations to iso-vector states to include rho and pi mesons. (See section E.1 below.) We also plan to apply the continuum iso-vector theory to $(e, e'p)$ reactions in the giant resonance region, and to compare our results with recent measurements by the UNH group (Calarco, *et al.*) on ^{16}C and ^{16}O. We will incorporate Hartree-Fock terms in some of these calculations.

We also intend to do preliminary work on relativistic shell model calculations, at the mean-field level, and study how to include negative energy states in the calculation. The inclusion of the negative energy sea-potential is completely absent from the non-relativistic shell-model theory, and represents new physics. It has not been done before. We have developed codes to calculate the particle-particle shell-model matrix elements at UNH, and also we have Lanczos diagonalization programs for shell-model calculations. So we are in a good position to investigate relativistic shell-model calculations.

Finally, we want to complete our work on variational methods for model field theories in the Schrödinger representation. (Section E.2 below.) We have formulated procedures to renormalize these variational wave functionals and have some results for the ϕ^4 field theory and for the σ-ω model.

Lawrence Janoo, a second year graduate student at UNH, has expressed interest in working in theoretical nuclear physics and on relativistic field theory. He is a talented student, capable of contributing to our research projects, and will add much to the group. Mr. Janoo will be ready to start on a Ph.D project beginning summer 1991. We also intend to collaborate with Jorge Piekarewicz at Indiana University Nuclear

Theory Center on the RPA work.

E.1 Relativistic RPA

The object of our work on relativistic RPA theory was to determine if such a theory could be developed within the framework of QHD-I and to see if the results were in agreement with experiment. We have now completed the initial stage of this work, and a paper, in collaboration with R. J. Furnstahl at the University of Maryland, has been accepted for publication.[71]

Our work on the RPA theory has lead to a much better understanding of how to do these relativistic calculations. One significant finding was to discover which diagrams to include in the calculation. When only Hartree terms are included in the mean-field calculation for the ground state, we found that we only needed the direct matrix elements for the RPA calculation. We also found that it is important to include particle-hole pairs that come from occupied negative energy states, and we discovered how to include these states in the calculation. The negative energy contributions were omitted from previous RPA calculations,[73] and add many more configurations to the already large number of particle-hole states. Such $(N, \overline{N})$ states become important in the relativistic picture because of the small value of the effective mass in the nuclear medium. (In the non-relativistic picture, we would say that correlations in the nuclear ground state shift single-particle strength to high excitation energies.) Demonstrating self-consistency was a major result of our work. We were able to prove that relativistic RPA was a conserving approximation, using the Baym-Kadanoff formalism,[72] as well as to demonstrate numerically that it was conserving. We used the same interaction for the Hartree calculation as for the RPA calculation so that it would be consistent.

We used a spectral approach to find the energies and electron scattering response functions for ^{12}C, ^{16}O, and ^{40}Ca. The advantage of this approach was to show how the results converge with the number of configurations. Exchange terms can easily be included with the spectral method. On the other hand, by solving a differential equation, non-spectral methods take into account all the unbound, as well as the negative energy states. In addition, the differential equation approach can be used for the continuum region of the spectrum.

We obtained good results for the iso-scalar collective natural parity states for these nuclei. We show the energy levels for ^{16}O in Fig. E.1 and some selected form factors in Figs. E.2 and E.3. More details can be found in our paper.[71] Recall that there are only four parameters in the model, which are fit to the nuclear matter saturation curve. The contributions of the negative energy holes is necessary to obtain agreement with the data. Our results agree with non-spectral calculations.[74]

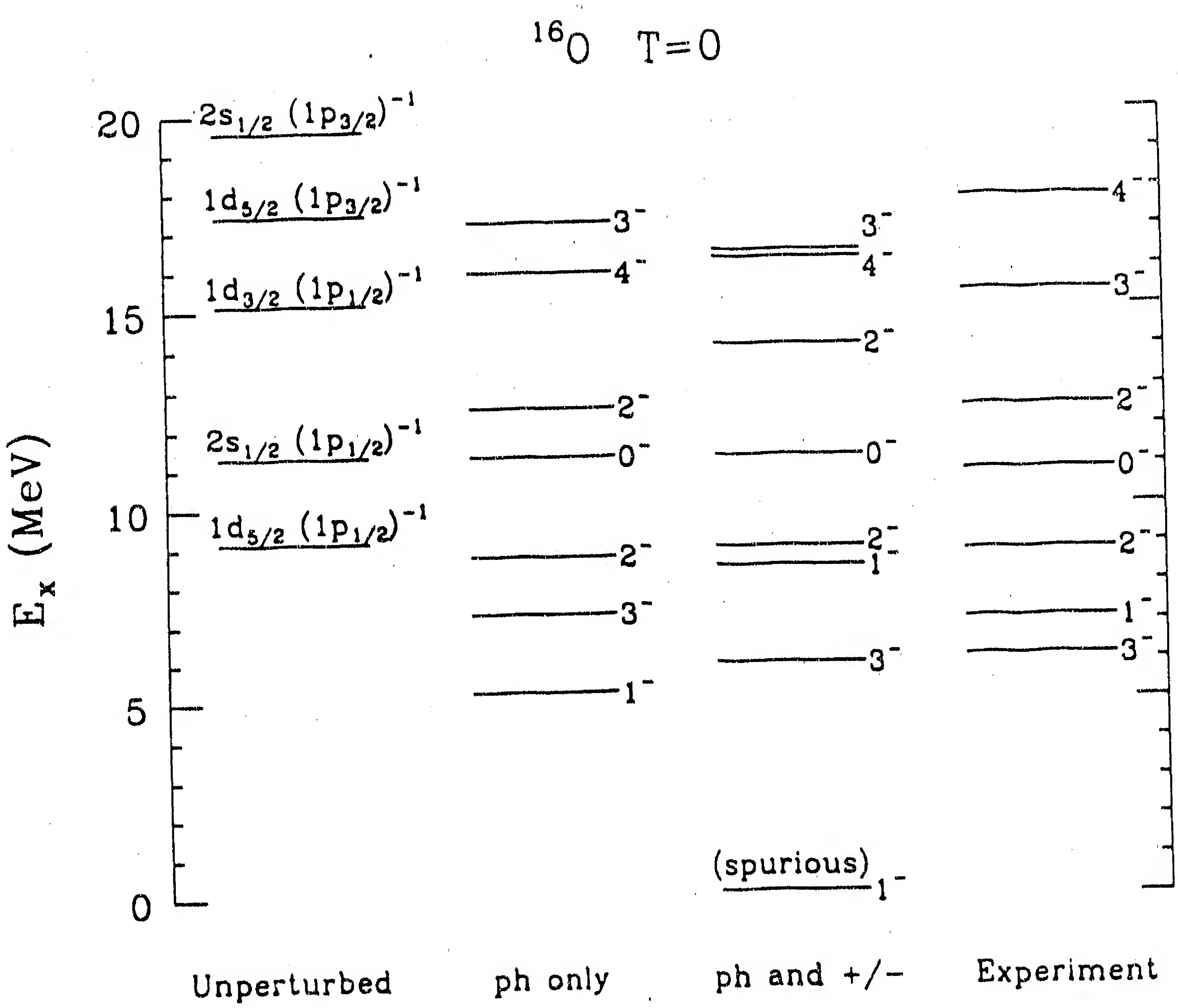

Fig. E.1 Energy levels of selected low-lying $T = 0$ states in ^{16}O for a spectral RPA calculation.

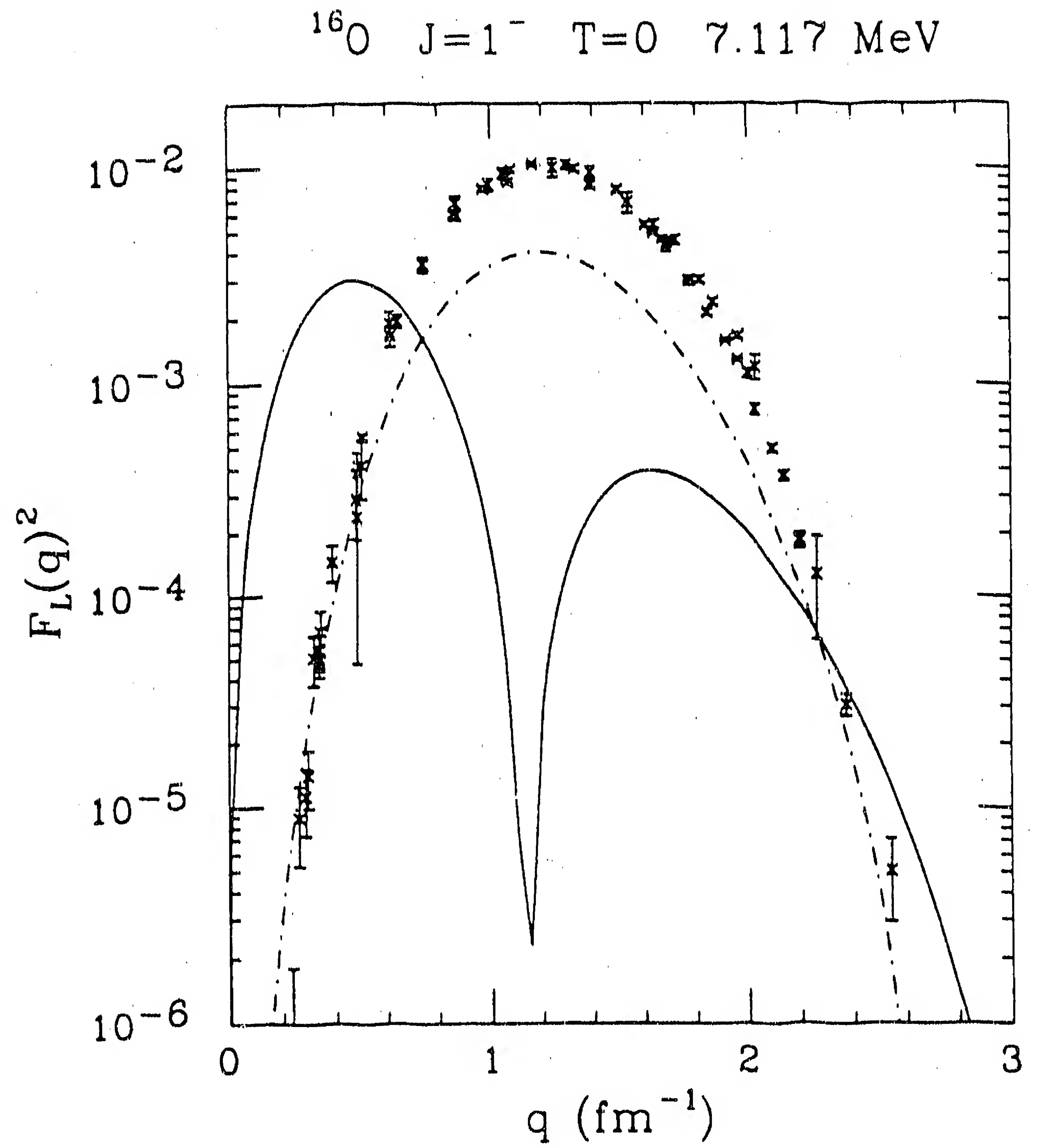

Fig. E.2 Longitudinal form factor for the 7.1 MeV isoscalar 1^- state in ^{16}O. The RPA curve (dot-dashed) is compared to an unperturbed $2s_{1/2}(1p_{1/2})^{-1}$ pair (solid) and to data.[75]

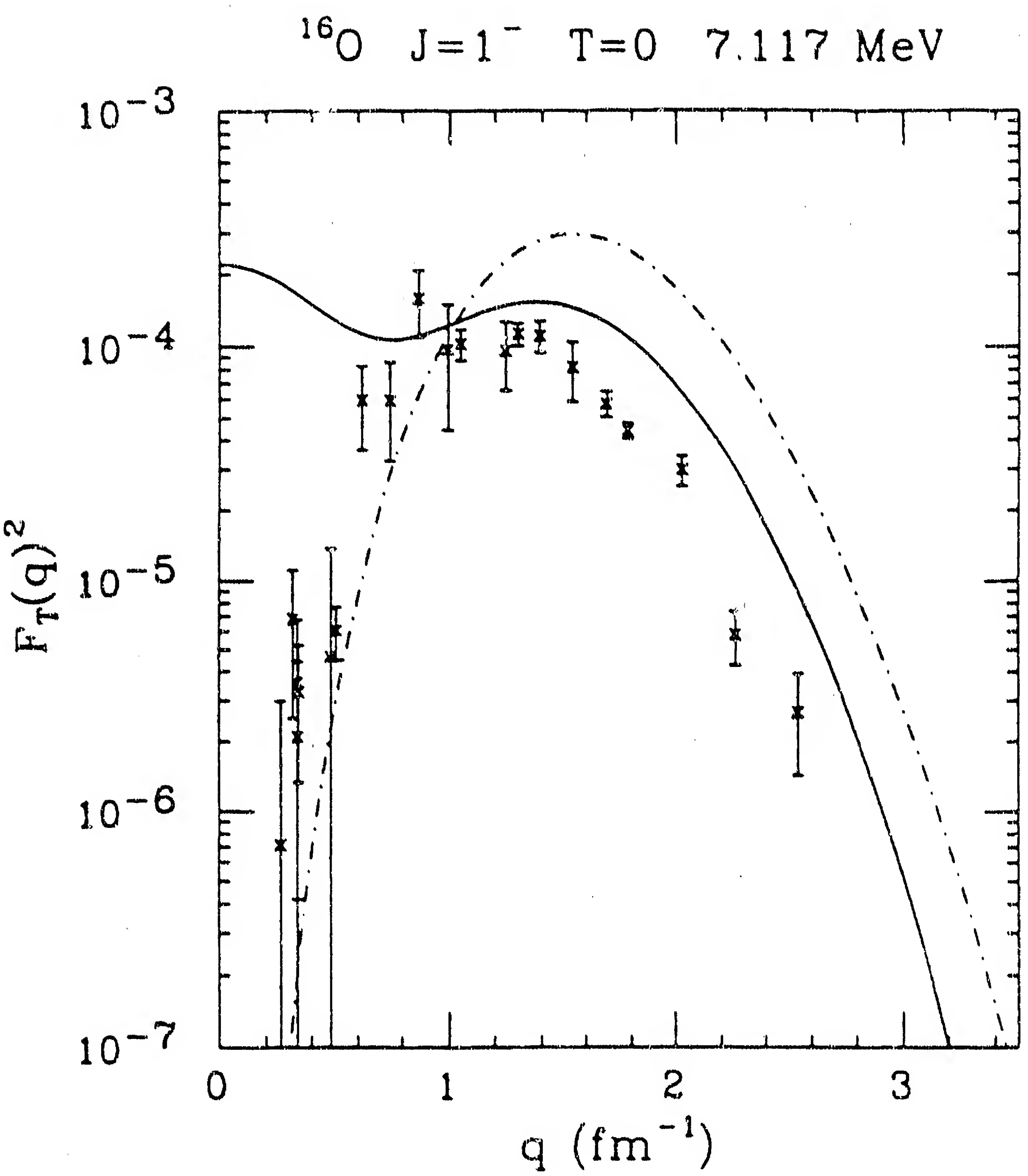

Fig. E.3 Transverse form factor for the 7.1 MeV isoscalar 1^- state in ^{16}O. The RPA curve (dot-dashed) is compared to an unperturbed $2s_{1/2}(1p_{1/2})^{-1}$ pair (solid) and to data.[75]

Recently, a local density approximation was used to compute the effects of the one-loop vacuum polarization corrections, using a non-spectral method.[76] At high momentum transfers, vacuum polarization effects become important. Charge is still conserved, but the total momentum is not. This is because of the local density approximation — a different potential is used in the relativistic Hartree approximation. It is important to find out if this will have serious consequence for the other states as well, since there is no known method to calculate vacuum polarization corrections in finite nuclei at present. These results have a direct bearing on the Coulomb sum problem for quasi-elastic electron scattering. We intend to explore the use of gradient expansion methods for finite nuclei. Such methods have been useful for vacuum polarization calculations for the Hartree model (See section E.2 below).

The only calculations for iso-vector states in the relativistic RPA model are for a small basis size without the negative energy contributions.[73] The iso-scalar part of the interaction is mostly determined by the Hartree mean-field. The iso-vector part is fixed by the symmetry energy and exchange energy. So parameters for the rho and the pi are not well known. Hartree-Fock calculations will require exchange terms in the RPA calculation. Calculations for small basis sets have shown that there are major differences between Hartree/RPA and Hartree-Fock/RPA.[73] In addition, charged pions should be added and additional charged meson currents computed for the anomalous part of the electromagnetic current operator. That is, we must face the problem of calculating iso-vector form factors in the medium. This calculation has never been done consistently. Another challange is that the pion provides a particularly attractive interaction in unnatural parity states (which have the pion quantum numbers), for pseudo-scalar coupling. Pseudo-vector coupling reduces the size of the pion contribution, but then renormalizability is sacrificed. A major effort is required to carry out this physics program.

We propose to work on the isovector-RPA problem in a series of stages: first, to try to use a non-spectral method to calculate the continuum RPA response by just including the extra mesons, and to determine the parameters by fixing them to nuclear matter properties. We intend to collaborate with Jorge Piekarewicz of the Nuclear Theory Center at the Indiana University Cyclotron Facility. Dr. Piekarewicz has new codes for non-spectral calculations of the particle-hole Green's functions. We will add couplings to the additional mesons into this code. Next, we hope to investigate the effects of the exchange terms. At UNH, we have codes for Hartree-Fock calculations which include the rho and pi for both pseudo-scalar and pseudo-vector coupling. In this case, we will do a spectral calculation with as large a basis as we can. Non-spectral Green's functions methods do not work for the exchange term. It may not be possible to do the continuum calculation here, we don't know. Finally, we want to study that part

of the form factor that is responsible for the anomalous current. Some of this comes from charged pion loops, and we will formulate methods for including such effects into the RPA calculation.

There are many levels of sophistication here, and it will be useful to see just how well we can do with the theory at various stages. In order to compare theory to experiment, however, it is necessary to understand the iso-vector part of the mean field. We expect to be able to shed some light on this important question.

In the continuum region, we have $(e, e'p)$ data taken at Bates by the UNH group (Calarco, *et al.*) for ^{12}C and ^{16}O.

E.2 Field Theory in the Schrödinger Representation

This work is in collaboration with Brian Hatfield of Applied Mathematical Physics Research, of Lexington, Mass.

We have been working on variational methods for field theories in the Schrödinger representation. The promise in this approach lies in the fact that, in principle, variational methods can be used for the strongly coupled fermi-bose field theories, such as QHD, which are of interest to nuclear physics. Loop expansions are perturbative. Variational solutions do not have to be. Thus by using variational wave functionals in the Schrödinger representation, we can avoid the loop expansion (which does not appear to converge for QHD). All properties of direct interest to nuclear physics can be calculated in the Schrödinger representation. So variational wave functionals represent a new and different approximation scheme — for both the ground states and excitation modes.

One of the challanges with variational methods in field theories has been that it is not known how to renormalize them. In order to study this problem, we started out with a "toy" field theory, the scalar ϕ^4 field theory. For certain gaussian wave functionals, we have been able to reproduce the loop expansion results, and can see how to do the renormalization in this picture.

For more general trial wave functionals, the renormalized results for the ϕ^4 theory do not give the same action as the loop expansion method, but we are not sure yet if the action is finite. We suspect that the action is in fact not finite, contrary to results published in the literature.[77,78] However, the ϕ^4 theory, after renormalization, is believed[79] to be a free field theory with vanishing renormalized coupling constant, so this model may be a special case. We plan to check these results with some numerical calculation, since the non-linear equations relating bare to renormalized quantities cannot be solved in closed form. We are preparing a paper on this subject.

For the case of QHD-I, we have obtained the functional Hamiltonian and have some trial wave functionals, and have worked out part of the renormalization methods. Good trial wave functionals for QHD-I are more difficult to find for the fermi (nucleonic) part, and we have only used the simplest ones so far.

Other parts of the mean-field QHD theory has not been worked out very well yet in the Schrödinger representation. For example, this method could be used to find out how to renormalize the time-dependent relativistic Hartree theory. The time-dependent fluctuations in the relativistic Hartree theory give the nuclear RPA collective excitations. At the very least, the Schrödinger representation should lead to new insight into ways to calculate quantities such as electromagnetic form factors in the nuclear medium, nucleon correlation functions, and collective modes. We intend to work on these more theoretically fundamental problems also.

Section F

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Section G

PUBLICATIONS: JULY, 1987 TO JUNE, 1990

G.1 Referreed Journals

1. "Missing-Energy Dependence of the Separated Response Functions for the Reaction $^{12}C(e, e'p)$," P. E. Ulmer, H. Baghaei, W. Bertozzi, K. I. Blomqvist, J. M. Finn, C. E. Hyde-Wright, N. Kalantar-Nayestanaki, S. Kowalski, R. W. Lourie, J. Nelson, W. W. Sapp, C. P. Sargent, L. Weinstein, B. H. Cottman, P. K. Teng, E. J. Winhold, M. Yamazaki, J. R. Calarco, F. W. Hersman, J. J. Kelly, M. E. Schulze, and G. Audit, *Phys. Rev. Lett.* **59** (1987) 2259.

2. "High-Resolution Inelastic Electron Scattering from ^{17}O," D. M. Manley, B. L. Berman, W. Bertozzi, T. N. Buti, J. M. Finn, F. W. Hersman, C. E. Hyde-Wright, M. V. Hynes, J. J. Kelly, M. A. Kovash, S. Kowalski, R. W. Lourie, B. Murdock, B. E. Norum, B. Pugh, and C. P. Sargent, *Phys. Rev.* **C 36** (1987) 1700.

3. "Ground State Proton Capture Reactions from 20 to 100 MeV," H. J. Hausman, S. L. Blatt, T. R. Donoghue, J. Kalen, W. Kim, D. G. Marchlenski, T. W. Rackers, P. Schmalbrock, M. A. Kovash, and A. D. Bacher, *Phys. Rev.* **C 37** (1988) 503.

4. "Proton Radiative Capture by ^{15}N, ^{16}O, ^{27}Al, and ^{28}Si," T. W. Rackers, S. L. Blatt, T. R. Donoghue, H. J. Hausman, J. Kalen, W. Kim, D. G. Marchlenski, M. Wiescher, M. A. Kovash, and A. D. Bacher, *Phys. Rev.* **C 37** (1988) 759.

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6. "Giant *E1* Resonances in ^{20}Ne Observed with the $^{19}F(\vec{p}, \gamma_0\gamma_1)^{20}Ne$ Reaction," P. M. Kurjan, J. R. Calarco, G. A. Fisher, and S. S. Hanna, *Phys. Rev.* **C37** (1988) 2281.

7. "Electroexcitation of the Δ Resonance in the $(e, e'p)$ Reaction," H. Baghaei, W. Bertozzi, K. I. Blomqvist, J. M. Finn, J. Flanz, C. E. Hyde-Wright, N. Kalantar-Nayestanaki, R. W. Lourie, J. Nelson, W. W. Sapp, C. P. Sargent, P. Ulmer, L. Weinstein, B. H. Cottman, P. K. Teng, E. J. Winhold, M. Yamazaki, J. R. Calarco, F. W. Hersman, C. Perdrisat, V. Punjabi, M. Epstein, and D. J. Margaziotis, *Phys. Rev.* **C39** (1989) 177.

8. "Radiative Proton Capture to Excited States in ^{16}O," J. D. Kalen, H. J. Hausman, A. Abduljalil, W. Kim, D. G. Marchlenski, J. P. McDermott, T. W. Rackers, S. L. Blatt, M. A. Kovash, and A. D. Bacher, *Phys. Rev.* **C 39** (1989) 340.

9. "Density Dependence of the Two-Nucleon Effective Interaction at 135 MeV," J. J. Kelly, W. Bertozzi, T. N. Buti, J. M. Finn, F. W. Hersman, C. Hyde-Wright, M. V. Hynes, M. A. Kovash, B. Murdock, B. E. Norum, B. Pugh, F. N. Rad, A. D. Bacher, G. T. Emery, C. C. Foster, W. P. Jones, D. W. Miller, B. L. Berman, W. G. Love, J. A. Carr, and F. Petrovich, *Phys. Rev. C* **39** (1989) 1222.

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11. "Transition Radii and Sum Rules in ^{238}U$(e, e'f)$," K. A. Griffioen, K. Van Bibber, and J. R. Calarco, *Phys. Rev. Lett.* **62** (1989) 689(C).

12. "Direct Measurement of the Branching Ratio Γ_n/Γ_f of ^{238}U in Inelastic Alpha Scattering in the Giant Resonance Region," P. J. Countryman, K. A. Griffioen, K. Van Bibber, M. R. Yearian, and J. R. Calarco, *Phys. Rev. C* **41** (1990) 1039.

13. "Quasielastic Reaction Mechanism Studied Using ^{12}C$(e, e'p)$," L. B. Weinstein, H. Baghaei, W. Bertozzi, J. M. Finn, J. Glickman, C. E. Hyde-Wright, N. Kalantar-Nayestanaki, R. W. Lourie, J. A. Nelson, W. W. Sapp, C. P. Sargent, P. E. Ulmer, B. H. Cottman, L. Ghedira, E. J. Winhold, J. R. Calarco, J. Wise, P. Boberg, C. C. Chang, D. Zhang, K. Aniol, M. B. Epstein, D. J. Margaziotis, C. Perdrisat, and V. Punjabi, *Phys. Rev. Lett.* **64** (1990) 1646.

14. "Electrofission in the Quasifree and Delta Regions," K. Hansen, J.-O. Adler, K. I. Blomqvist, D. Nilsson, A. Sandell, B. Schroder, W. R. Dodge, J. W. Lightbody, Jr., J. S. O'Connell, J. R. Calarco, J. P. Connelly, F. W. Hersman, W. Kim, and M. Leuschner, *Phys. Rev. C* **41** (1990) 1619.

15. "Effective Interactions on Nuclear Structure Using 180 MeV Protons I: ^{16}O(p, p')," J. J. Kelly, J. M. Finn, W. Bertozzi, T. N. Buti, F. W. Hersman, C. Hyde-Wright, M. V. Hynes, M. A. Kovash, B. Murdock, P. Ulmer, A. D. Bacher, G. T. Emery, C. C. Foster, W. P. Jones, D. W. Miller, and B. L. Berman, *Phys. Rev. C* **41** (1990) 2504.

16. "Electron Scattering from ^{92}Mo," T. E. Milliman, J. P. Connelly, J. H. Heisenberg, F. W. Hersman, J. E. Wise, and C. N. Papanicolas, *Phys. Rev. C* **41** (1990) 2586.

17. "Proton Core Polarization in Low-lying States of ^{86}Sr," J. P. Connelly, T. E. Milliman, J. H. Heisenberg, F. W. Hersman, J. E. Wise, and C. N. Papanicolas,

Phys. Rev. C accepted for publication.

18. "Single Particle Excitations in ^{89}Y," J. E. Wise, F. W. Hersman, J. H. Heisenberg, T. E. Milliman, J. P. Connelly, J. R. Calarco, and C. N. Papanicolas, *Phys. Rev. C* accepted for publication.

19. "Relativistic Spectral RPA in Finite Nuclei," J. F. Dawson and R. J. Furnstahl, *Phys. Rev. C* accepted for publication.

G.2 Invited Talks

1. "Electron Scattering and Nuclear Structure," J. H. Heisenberg, in "Electron Scattering: Past and Future," *Proceedings of the Sixth Mini-conference* Amsterdam, (November 1989) 55

2. "Electron Scattering in the Extended Shell Model," J. H. Heisenberg, Proceedings of the workshop held at OSU on the "Relativistic Nuclear Many-Body Physics," June, 1988.

3. "Densities Extracted from Electron Scattering," J. H. Heisenberg, International Study Conference on Nuclear Physics held in Eilat, Israel, January, 1988

4. In addition, J. Heisenberg presented seven colloquia or seminars on similar topics.

5. "Two Nucleon Correlation Studies at NIKHEF: Status of the Planned $(e, e'2p)$ Experiment," J. R. Calarco, *Institut für Kernphysik, Mainz, West Germany, Research Seminar*, November, 1988.

6. "Coincidence Experiments and Studies of Quasielastic $(e, e'p)$ Reactions," J. R. Calarco, *Institute Jožef Stefan, Ljubljana, Yugoslavia, Seminar*, February, 1989.

7. "CEBAF, A Facility for Nuclear Physics in the 1990's and Beyond," J. R. Calarco, *Institute Jožef Stefan, Ljubljana, Yugoslavia, Colloquium*, March, 1989.

8. "Coincidence studies of $(e, e'x)$ reactions at Mainz; Giant Resonance Excitation and Decay," J. R. Calarco, *C.E.A., Saclay, France, Seminar*, April, 1989.

9. "Nuclear Transition Densities from Electron Scattering", F. W. Hersman, Workshop on Nuclear Structure with Intermediate Energy Probes, Santa Fe, New Mexico, October, 1988.

10. "What's New in Inelastic Electron Scattering?", F. W. Hersman, Gordon Research Conference on Photonuclear Reactions, Plymouth, New Hampshire, August 1988.

11. "Subatomic Particles, Accelerators, and Splitting the Atom", F. W. Hersman, Zone Meeting of the Society of Physics Students, Worcester, MA, February, 1988.
12. "Scattering Investigations of Nuclear Transition Densities", F. W. Hersman, International Conference on Nuclear Structure Through Static and Dynamic Moments, Melbourne, Australia, August 1987.
13. "The Bates Large Acceptance Spectrometer Toroid," F. W. Hersman, Workshop on Multinucleon Emission Reactions, Elba, Italy
14. "The Bates Large Acceptance Spectrometer Toroid," F. W. Hersman, Bates Linear Accelerator Users Group Meeting, Asilomar, CA, October 1989.
15. "The Bates Large Acceptance Spectrometer Toroid," F. W. Hersman, Bates Linear Accelerator Users Group Meeting, Middleton, MA, January, 1990.
16. "The Bates Large Acceptance Spectrometer Toroid," F. W. Hersman, DOE Site Review, Bates Accelerator, Middleton, MA, January, 1990
17. "Physics with a BLAST," F. W. Hersman, Bates Accelerator seminar, September, 1989
18. "Evidence for Nuclear Correlations in Electron Induced Reactions", F. W. Hersman, University of Kentucky, Lexington, KY, March 1989.
19. "Evidence for Nuclear Correlations in Electron Induced Reactions", F. W. Hersman, University of Pittsburgh, Pittsburgh, PA, March 1989.
20. "Studies of Two-Nucleon Correlations", F. W. Hersman, MIT-Bates Linear Accelerator, Middleton, MA, February, 1989.
21. "Scattering Investigations of Nuclear Structure", F. W. Hersman, Massachusetts Institute of Technology, Cambridge, MA, November 1987.
22. "Single Nucleon and Multinucleon Properties of the Nucleus, Observed from Electron Scattering Experiments", M. Leuschner, *Institut für Kernphysik, Mainz, West Germany, Colloquium*, June, 1989

G.3 Abstracts

1. "Study of α Decay from the Giant Resonance Region of ^{12}C Using the ^{12}C$(e,e'\alpha)$ Reaction," with D. DeAngelis, *et al.*, *BAPS* **32** (1987) 1573.
2. "Non-spherical Components in the ^{16}O Ground State Wave Function", M. Leuschner *et al., BAPS* **33** (1988) 1097.
3. "Giant Resonances on Excited States in ^{15}O observed in ^{3}He Capture," with S. L. Blatt, *et al.*, BAPS **33** (1988) 1575.

4. "The ^{4}He$(e, e'p)$ Reaction at 260 MeV/c Recoil Momentum," with M. B. Epstein, *et al.*, *BAPS* **33** (1988) 1594.

5. "Q^2 and Target Dependence of the $(e, e'p)$ Reaction," with P. Boberg, *et al.*, *BAPS* **33** (1988) 1594.

6. "α-Emission nach Elektroanregung von ^{16}O im Bereich der Dipolriesenresonanz," mit J. P. Fritsch, *et al.*, *Proc. DPG*, March, 1989.

7. "Untertsuchung der Reaktion ^{6}Li$(e, e'p_0)^5$He," mit A. Grasmück, *et al.*, *Proc. DPG*, March, 1989.

8. "Electro-excitation of the 0_2^+ state in ^{48}Ca", J. E. Wise, *et al., BAPS* **35** (1989) 927.

9. "High Resolution Electron Scattering from ^{208}Pb", J. P. Connelly *et al., BAPS* **34** (1989) 1152.

10. "Ground State Magnetization in ^{89}Y," J. E. Wise, *et al.*, *BAPS* **34** (1989) 1152.

11. "Q^2 and Target Dependence of the $(e, e'p)$ Reaction," with P. Boberg, *et al.*, *BAPS* **34** (1989) 1153.

12. "Inelastic Electron Scattering from ^{118}Sn", J. E. Wise, *et al., BAPS* **34** (1989) 1153.

13. "Inelastic Electron Scattering from ^{142}Ce," W. Kim, *et al.*, *BAPS* **34** (1989) 1153.

14. "Quasi-elastic Proton Knockout from the ^{16}O Ground State", M. Leuschner *et al., BAPS* **34** (1989) 1153.

15. "Study of Alpha Decay from the Giant Resonance region of ^{12}C Using the ^{12}C$(e, e'\alpha)$ Reaction," D. J. DeAngelis, *et al.*, *BAPS* **34** (1989) 1833.

16. "Study of Proton Decay from the Giant Resonance region of ^{12}C Using the ^{12}C$(e, e'p)$ Reaction," with G. E. Dodge, *et al.*, *BAPS* **34** (1989) 1833.

17. "Electro-excitation of the 0_2^+ State in ^{48}Ca", J. E. Wise, *et al.*, BAPS **35** (1990) 927.

18. "The Deep Inelastic $^{12}C(e, e'pp)$ Reaction", M. Leuschner *al., BAPS* **35** (1990) 928.

19. "Quasielastic Electron-induced Proton Knockout from Nonspherical Components of the ^{16}O Ground State Wave Function", M. Leuschner *et al., PANIC XII* (1990).

20. "Multinucleon knockout experiments using the Bates Large Acceptance Spectrometer Toroid", F. W. Hersman and M. Leuschner, *PANIC XII* (1990).

21. "The Triple Coincidence Reaction $^{12}C(e,e'pp)$ in the Delat-Excitation Region", A. Zondervan *et al., PANIC XII* (1990).
22. "Separation of the Longitudinal and Transverse Amplitudes for the Giant Dipole Resonances of ^{12}C and ^{16}O from Measurement of the $(e,e'p_0)$ Angular Correlations," J. R. Calarco, *PANIC XII,* (1990).
23. "Energy Dependence of Dispersive Effects in ^{12}C", N. Kalantar-Nayestanaki, *et al., PANIC XII* (1990).
24. "Bates Large Acceptance Spectrometer Toroid (BLAST) for $(e,e'p\pi)$ Measurements," W. Kim, *et al., PANIC XII* (1990).
25. "Interplay Between Single-Particle and Collective Degrees of Freedom in the Low-Lying Excitations of ^{142}Ce," W. Kim, *et al., PANIC XII* (1990).
26. "Measurements of Spin-Dependent Electron Scattering from a Polarized ^{3}He Internal Target and a Large Acceptance Detector," J. F. J. van den Brand, *et al., PANIC XII* (1990).

END

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